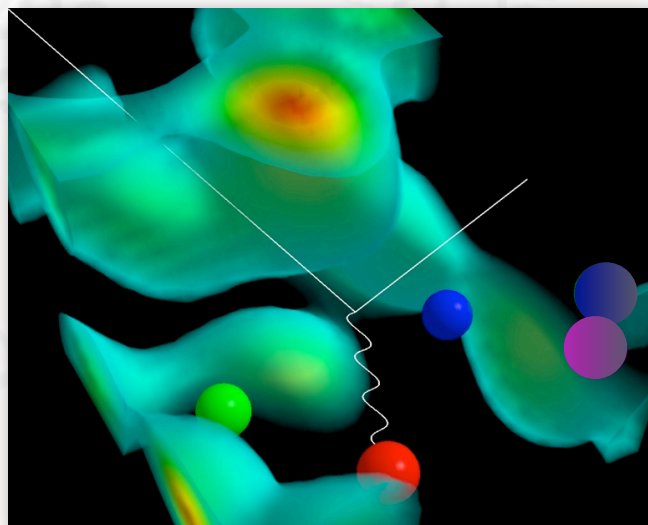


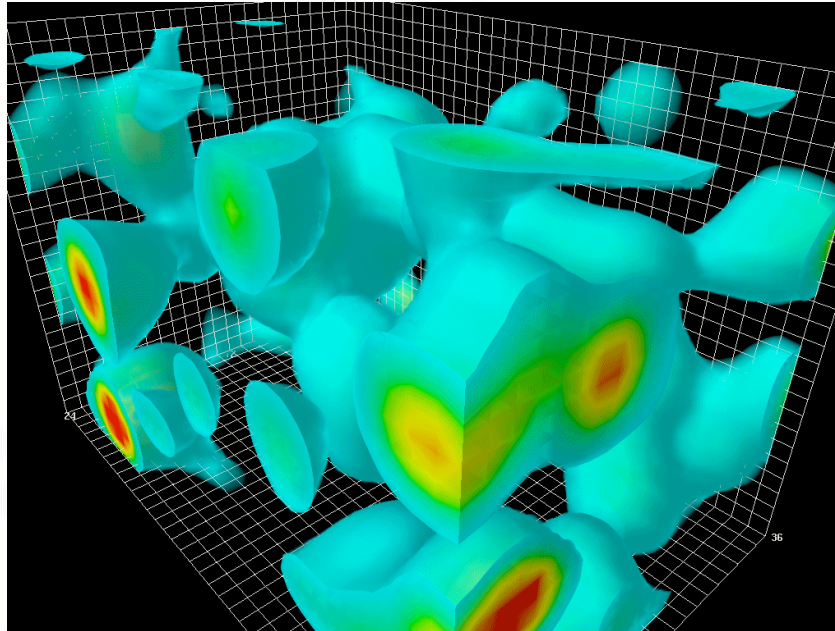


Experimental aspects on Low- x Physics at a Future EIC facility - Concepts / Status / Projections -

Bernd Surrow



Motivation



(D. Leinweber: Action (\sim energy) density fluctuations of gluon-fields in QCD vacuum)

Structure and **dynamics** of proton (**mass** / **spin**) (\rightarrow visible universe) originates from QCD-interactions!

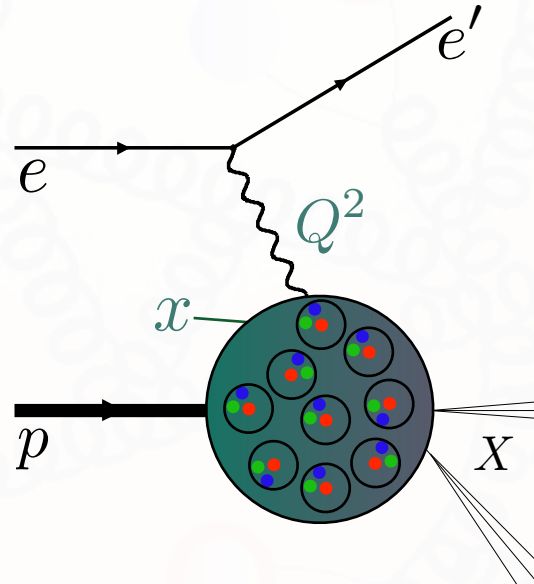
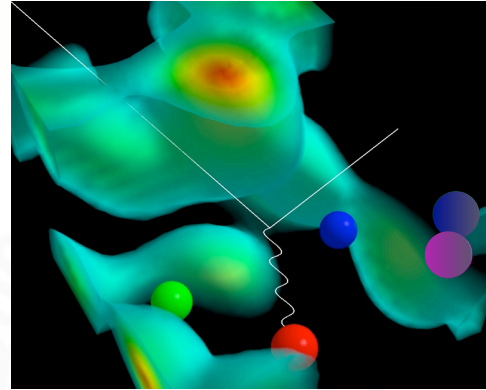
Synergy of **experimental progress** and **theory** (Lattice QCD / Phenomenology incl. **phenomenological fits** / **Modeling**) critical!

Motivation

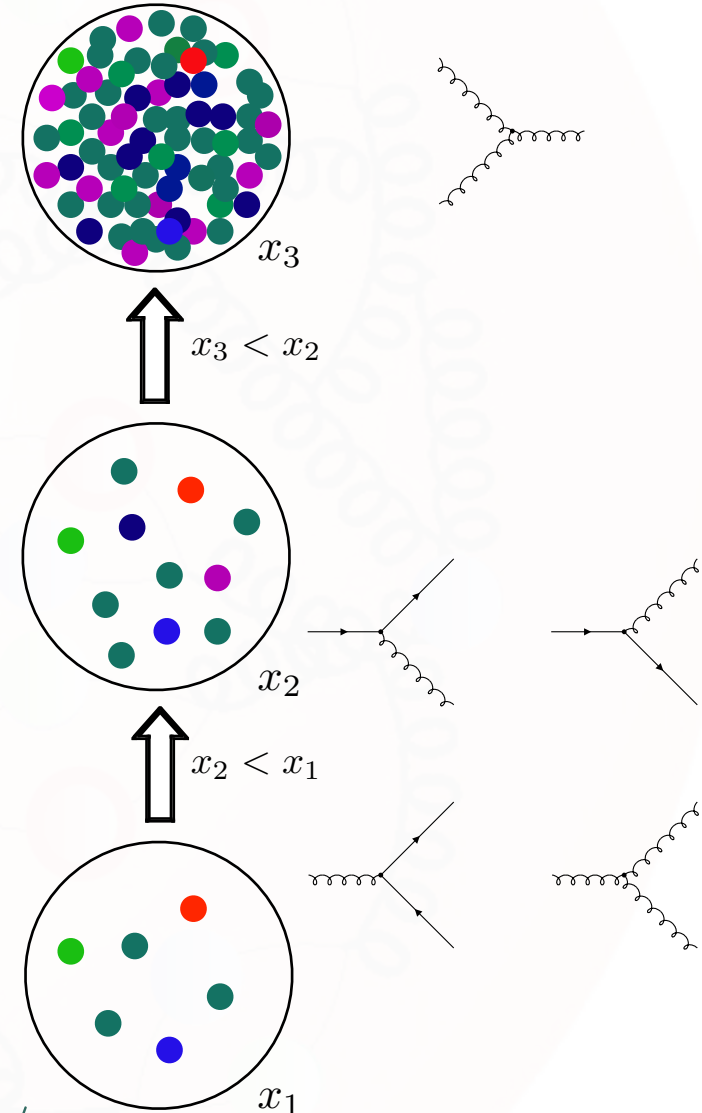
- The silent (low x) partners...: *Gluons* and *QCD-Sea*

Fundamental questions:

- What are the properties of *gluons* that bind strongly interacting particles?
- What is the *quark-gluon* internal structure of nucleons?
- What are the properties of *quark-gluon* matter at high density?



$$W^2 \simeq Q^2/x$$



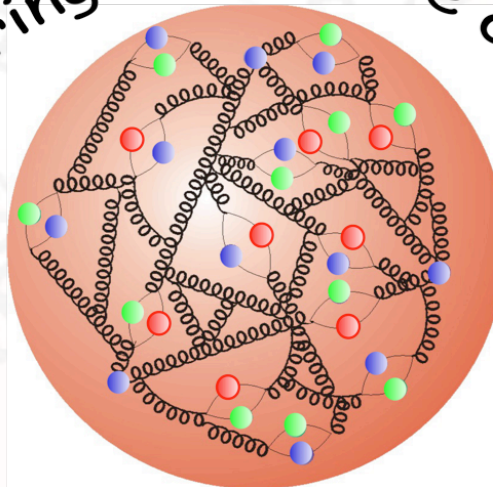
Outline

- Future unpolarized low- x opportunities:
Unpolarized ep/eA physics

- Future polarized low- x opportunities:
Polarized ep physics

Exploring the nature of glue

- Concepts and Status



- Summary and Outlook

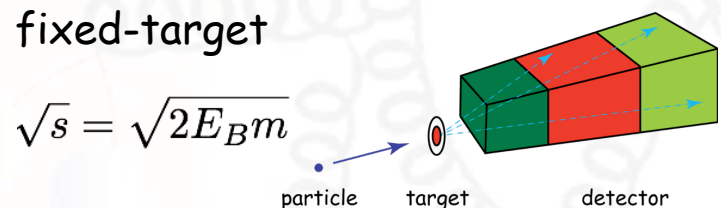
Concepts and Status

□ Low-x kinematics

○ Access higher parton density system

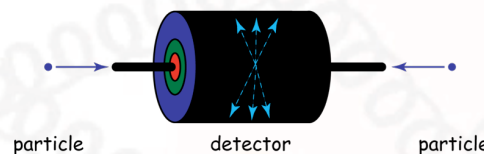
□ Larger center-of-mass energy (\sqrt{s}): Smaller x at larger \sqrt{s} !

fixed-target



$$\sqrt{s} = \sqrt{2E_B m}$$

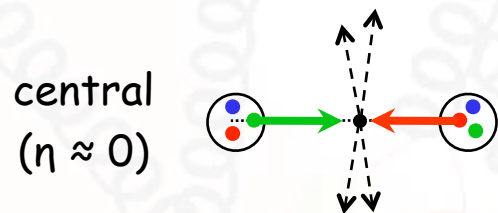
$$x \sim \frac{Q^2}{s}$$



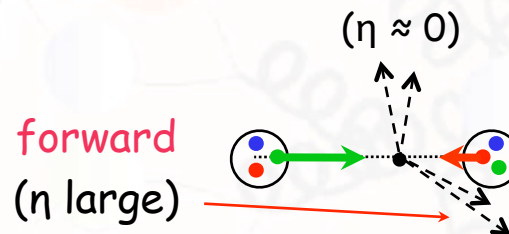
collider

$$\sqrt{s} = \sqrt{4E_{b1} E_{b2}}$$

□ Forward direction: Smaller x at larger η !

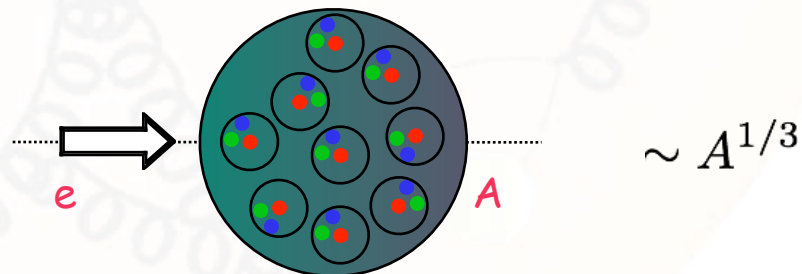
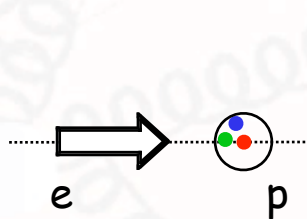


$$x \sim \frac{2p_T}{\sqrt{s}} e^{-\eta}$$



($\eta \approx 0$)

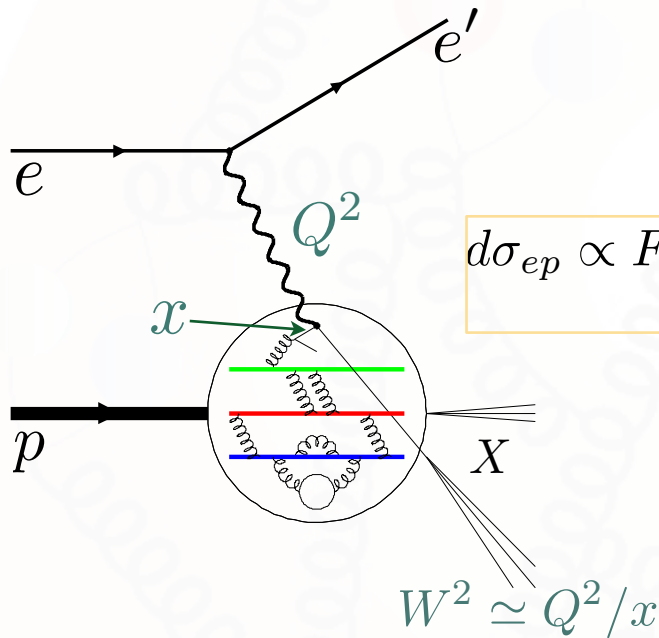
□ eA vs. ep scattering: Probe higher parton density system in eA compared to ep!



$$\sim A^{1/3}$$

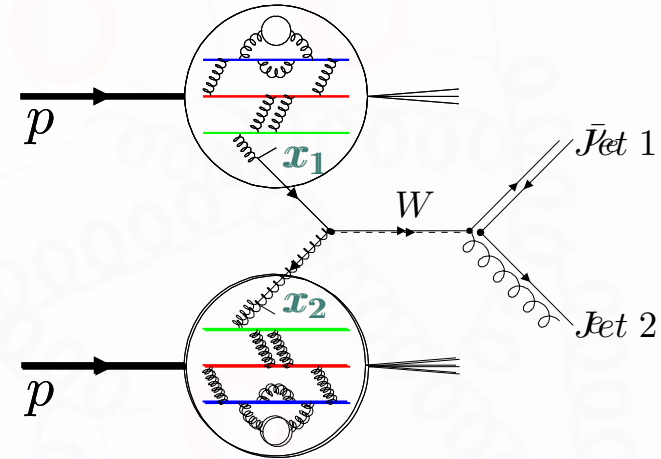
Concepts and Status

- Probing the structure and dynamics of matter in ep vs. pp scattering



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

Universality



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

Factorization

Momentum contribution

$$f(x) =$$

$$f^+(x) + f^-(x)$$

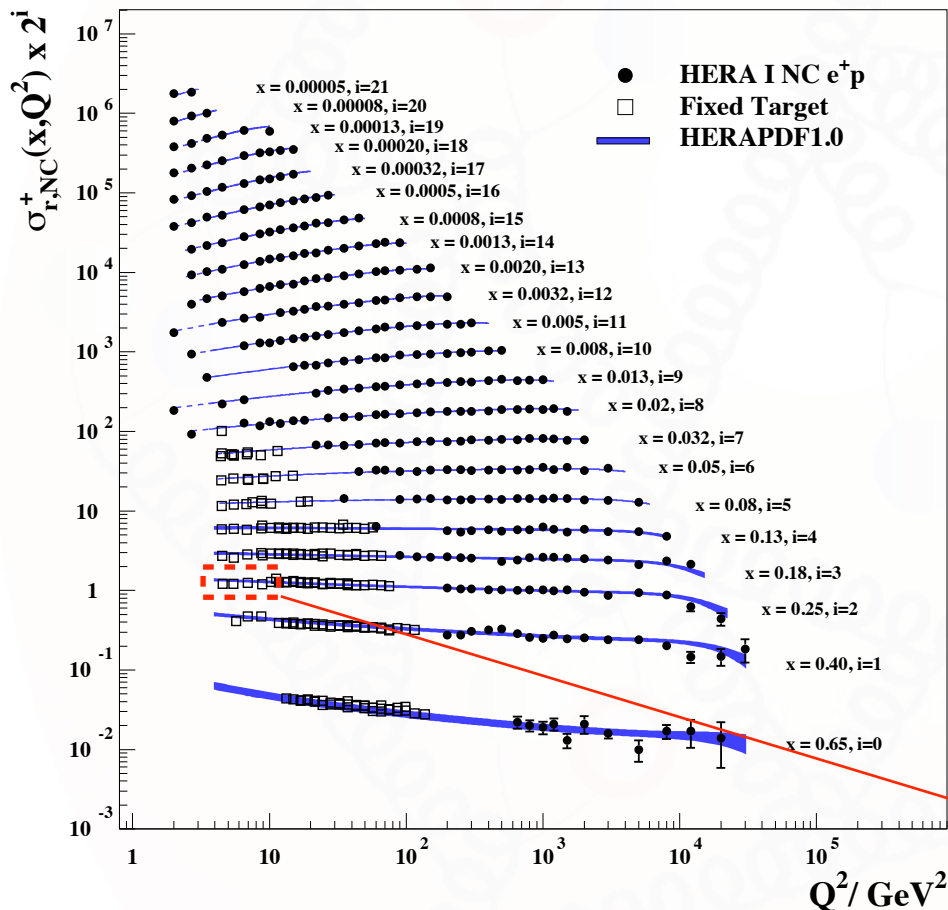
Spin contribution

$$\Delta f(x) =$$

$$f^+(x) - f^-(x)$$

Concepts and Status

- Picture of the proton from unpolarized ep scattering
H1 and ZEUS

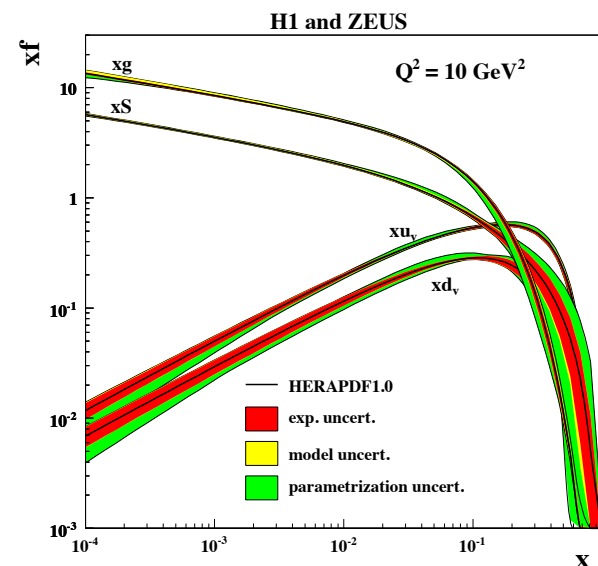
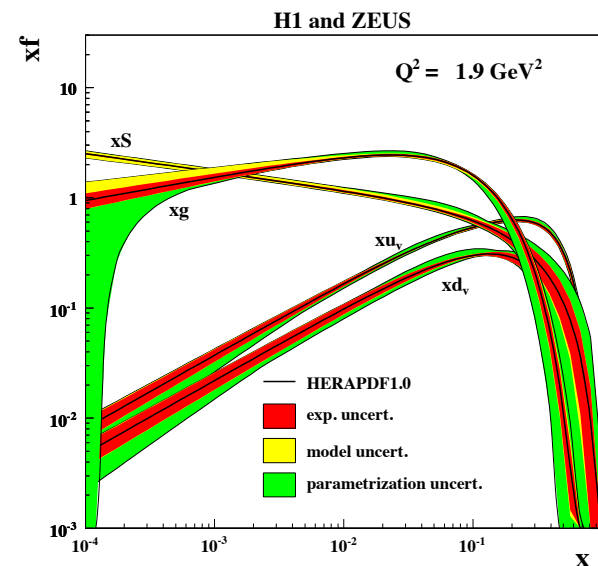


Strong violation of scaling at low x and high Q^2

In contrast to:

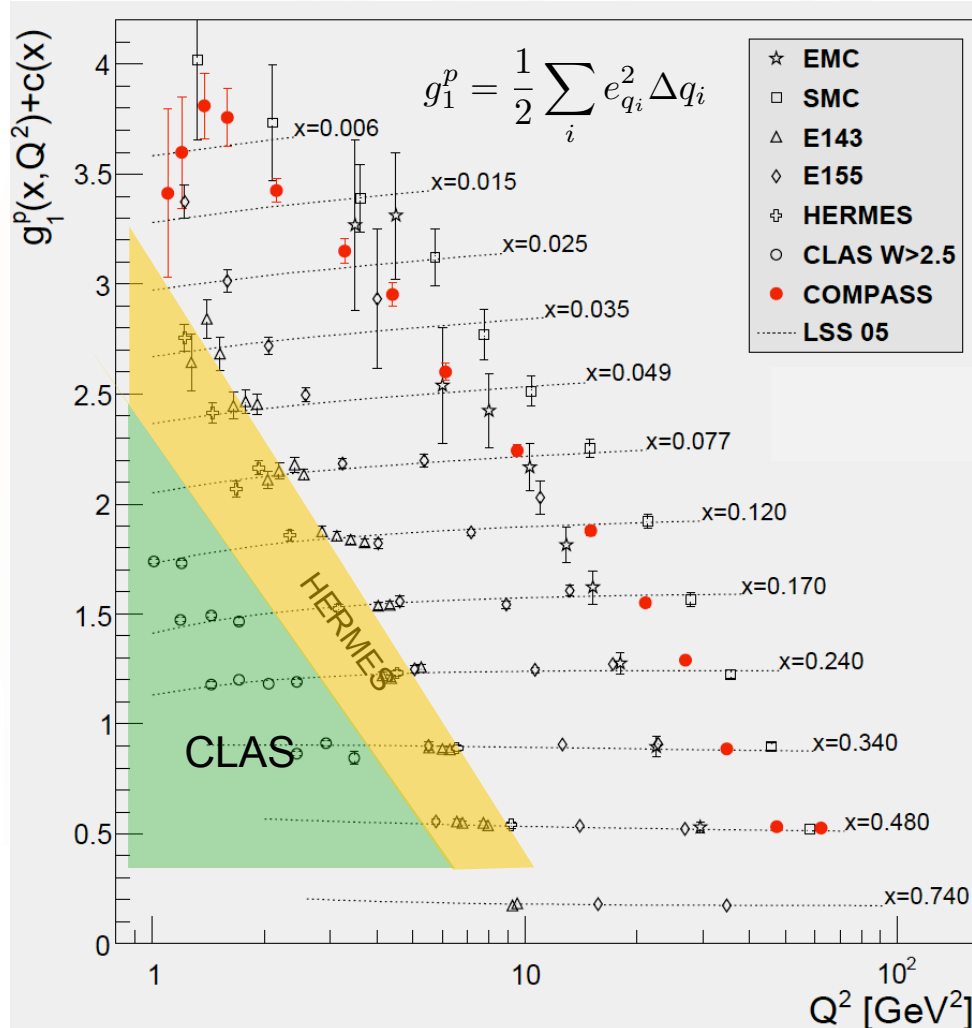
Low Q^2
high x !

Huge gluon and QCD sea contribution!



Concepts and Status

Picture of the proton from polarized ep scattering



Spin sum rule:

$$\frac{1}{2} \Delta \Sigma$$

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

$$\Delta G$$

(R.L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990))

$$\Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$$

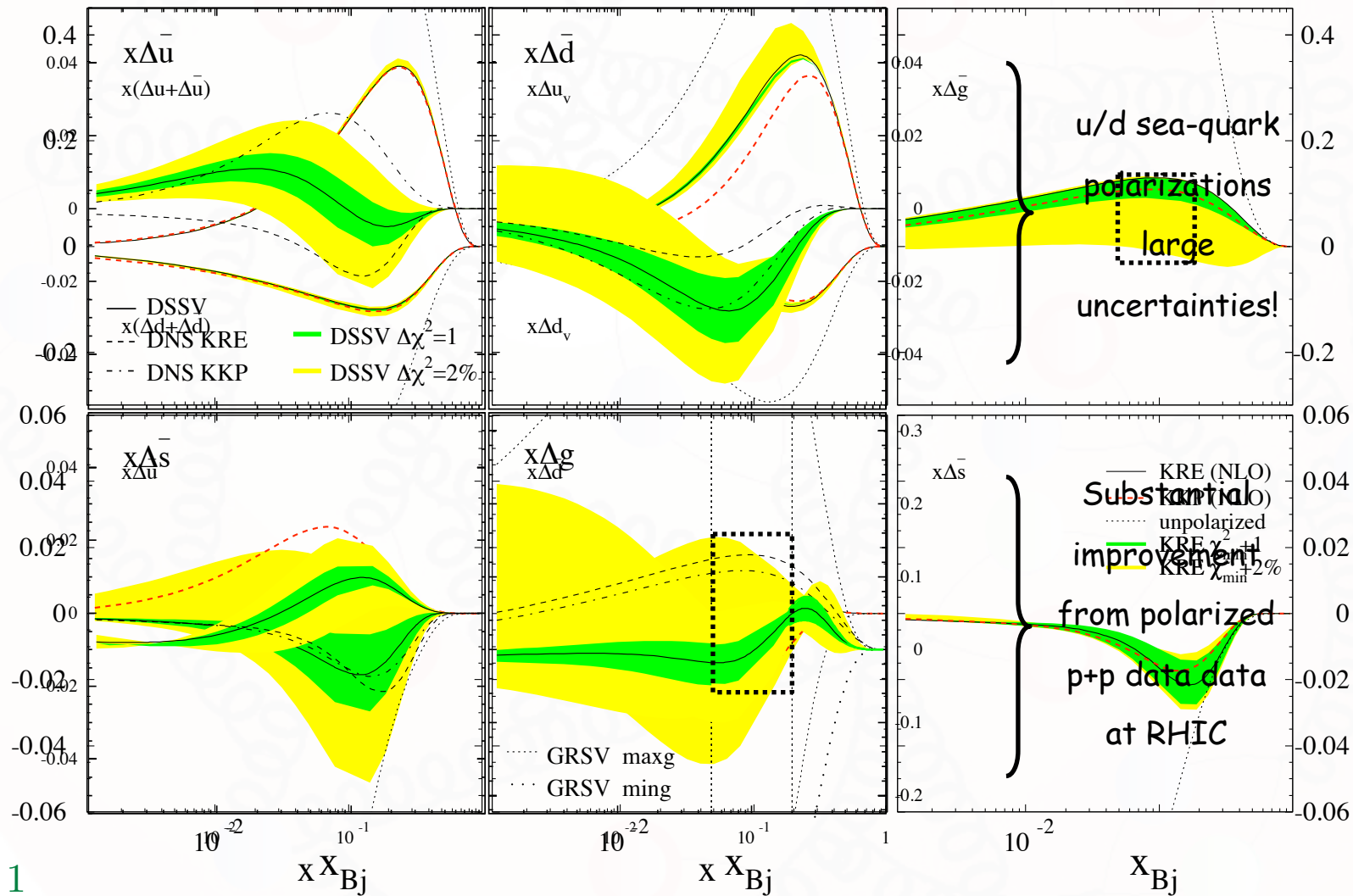
$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2) dx \quad \Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

Current status:

- Data only from **fixed-target experiments** (Limited reach in x and Q^2) mostly at lower energy
- **Quark spin contribution is small (~25%):**
 $\Delta \Sigma = 0.242 \quad (Q^2 = 10 \text{ GeV}^2)$
 (D. deFlorian et al., Phys. Rev. D80, 034030 (2009))
- **Gluon spin contribution unconstrained** from inclusive polarized ep scattering!

Concepts and Status

- Status: Polarization of quarks and gluons from a global QCD analysis

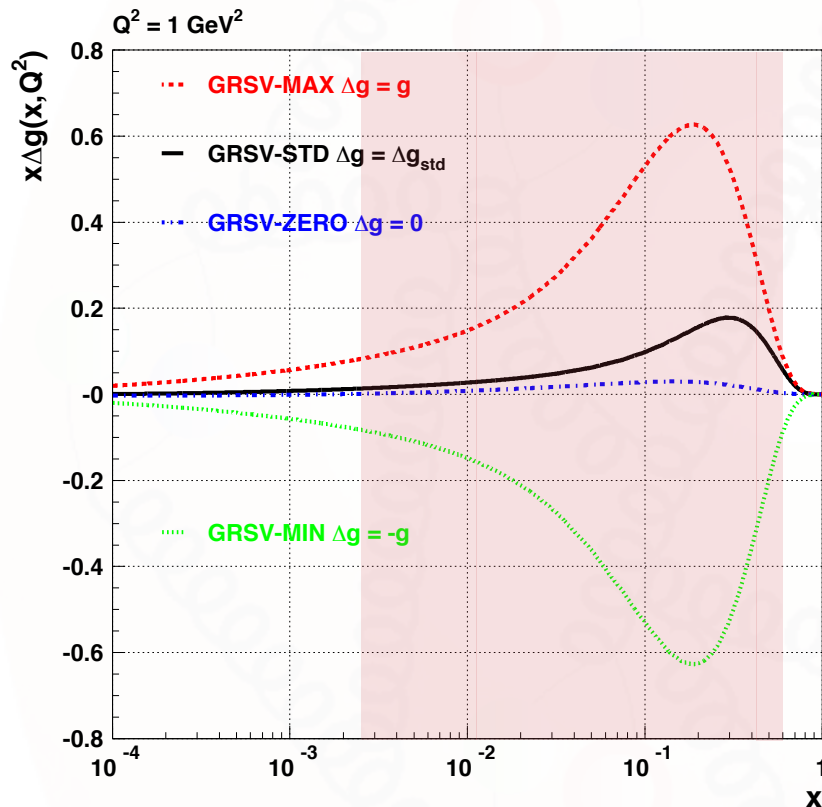


$\Delta\chi^2 = 1$

D. de Florian et al., Phys. Rev. Lett. 101 (2008) 072001
D. de Florian et al., Phys. Rev. D71, 094018 (2005).

Concepts and Status

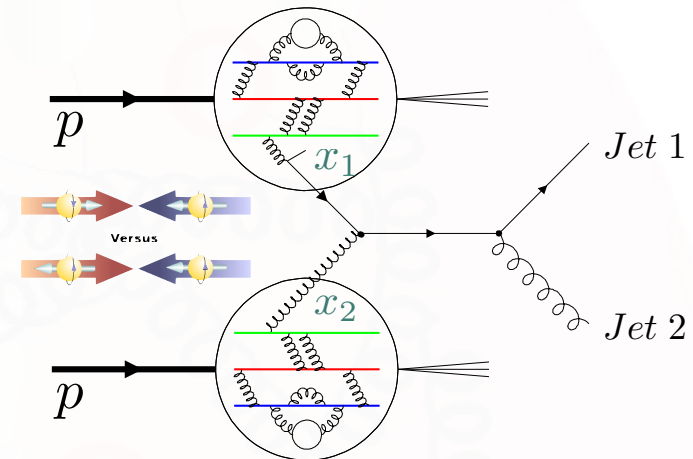
□ Connection of Δg and A_{LL} in pol. pp collisions at RHIC



$$\Delta G(Q^2 = 1 \text{ GeV}^2) \approx 1.8$$

$$\Delta G(Q^2 = 1 \text{ GeV}^2) \approx 0.4$$

$$\Delta G(Q^2 = 1 \text{ GeV}^2) \approx 0.1$$

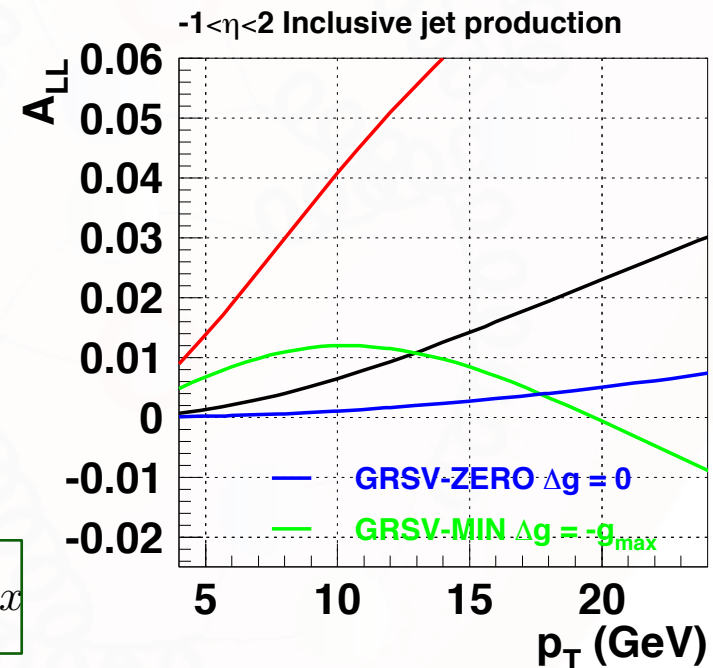


○ Examine wide range in Δg : $-g < \Delta g < +g$

○ GRSV-STD: Global QCD analysis of polarized DIS experiments only!

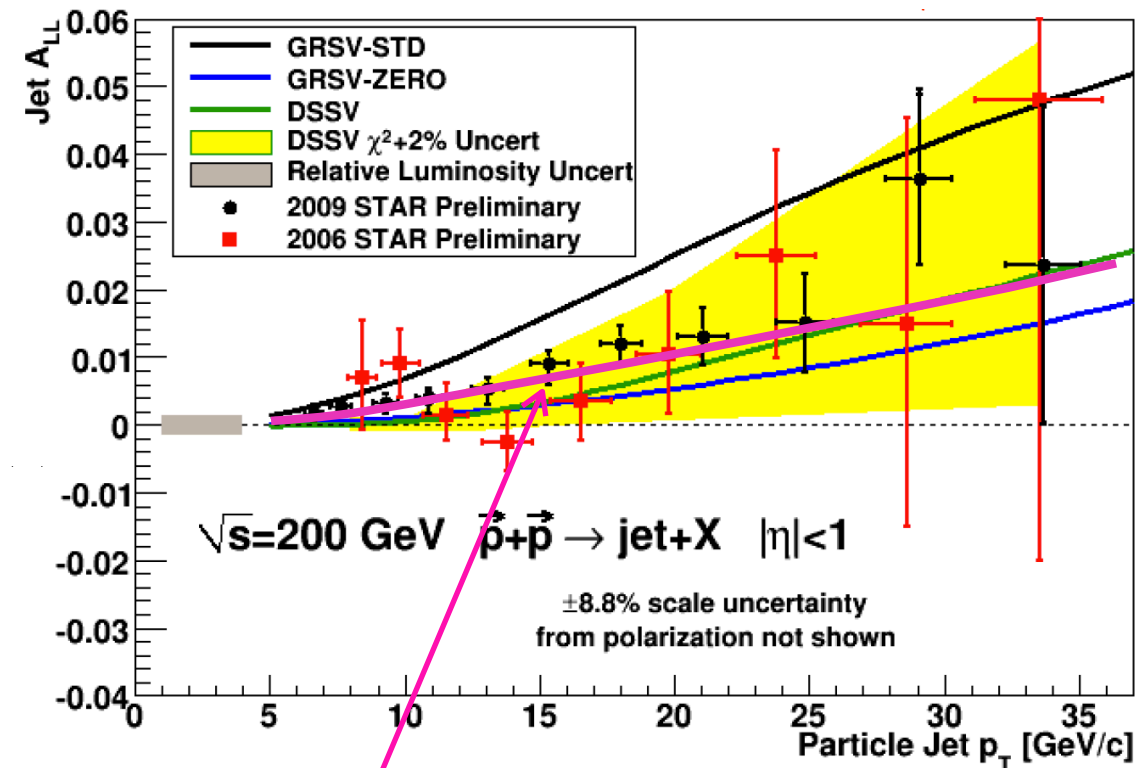
M. Gluck et al. PRD 63 (2001) 094005.

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$



Concepts and Status

□ RHIC A_{LL} result: STAR Mid-rapidity Inclusive Jet production

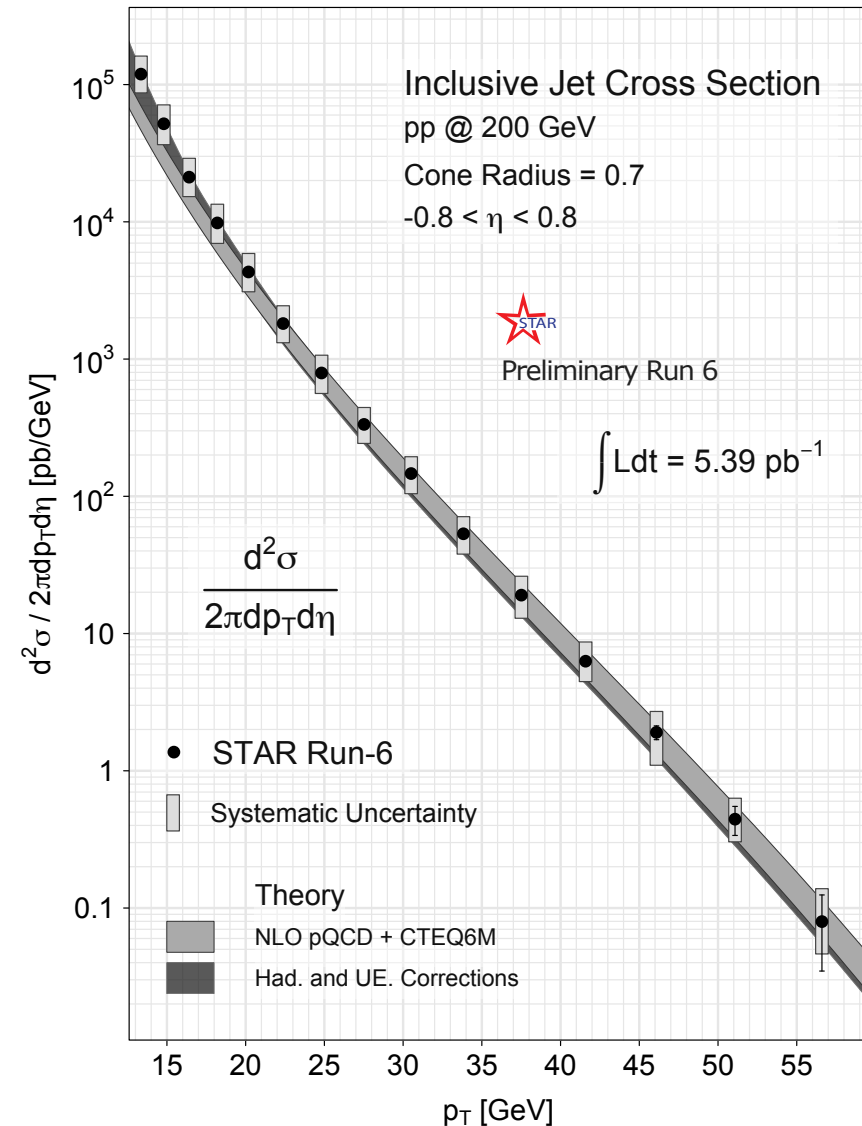


○ Data are well described by NLO pQCD plus hadronization corrections

$$\int_{0.05}^{0.2} dx \Delta g \approx 0.1 \text{ sections}$$

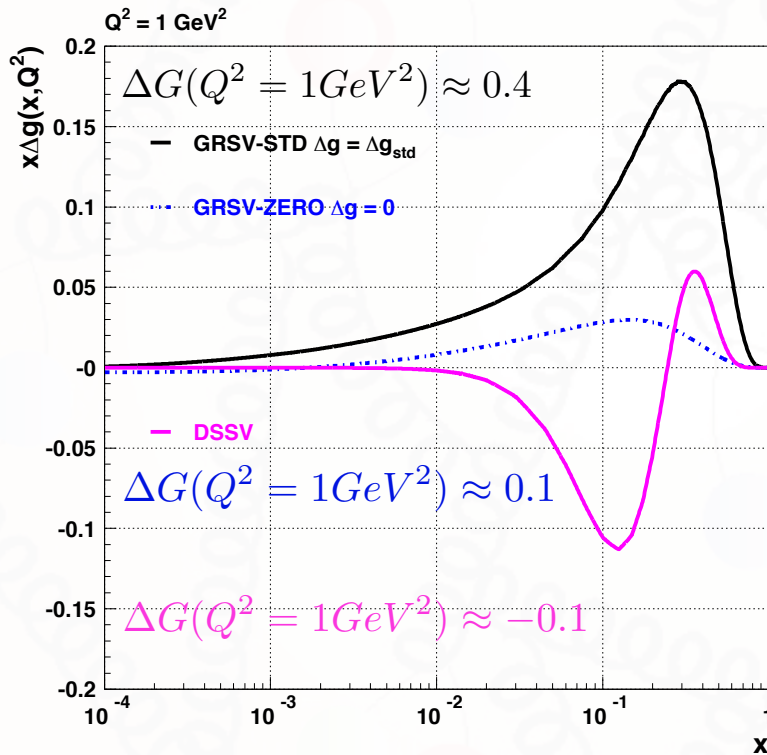
○ Run 0 A_{LL} measurement between GRSV-STD and GRSV-ZERO

○ Run 9 A_{LL} measurement between GRSV-STD and DSSV

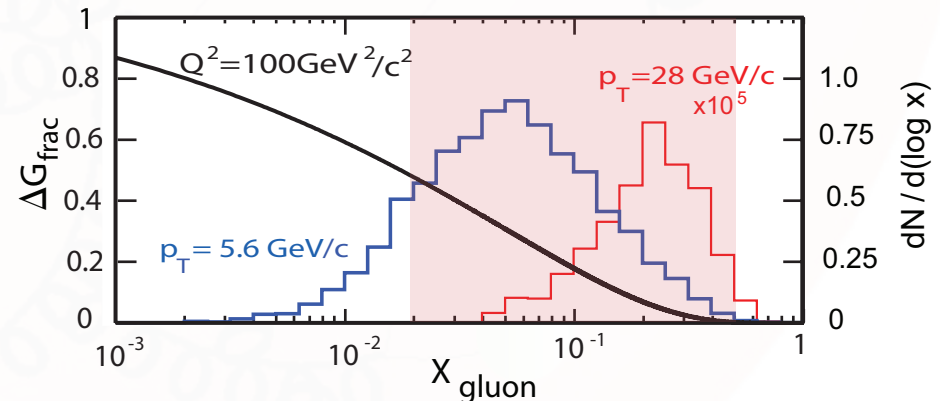
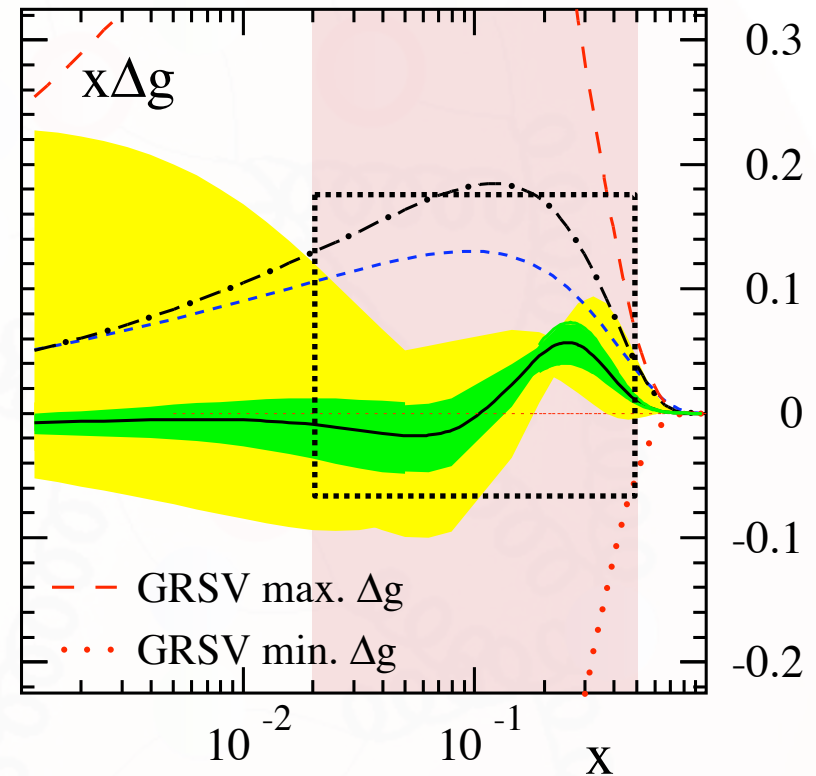


Concepts and Status

Results on Δg from DSSV fit incl. RHIC data



- Strong constraint on the size of Δg from RHIC data, in particular STAR jet results (Run 9)
- Strong indication for a small gluon polarization, but $\neq 0$
- Next steps:** Mapping of x -dependence and extension of x -coverage needed (Di-Jet measurements)!



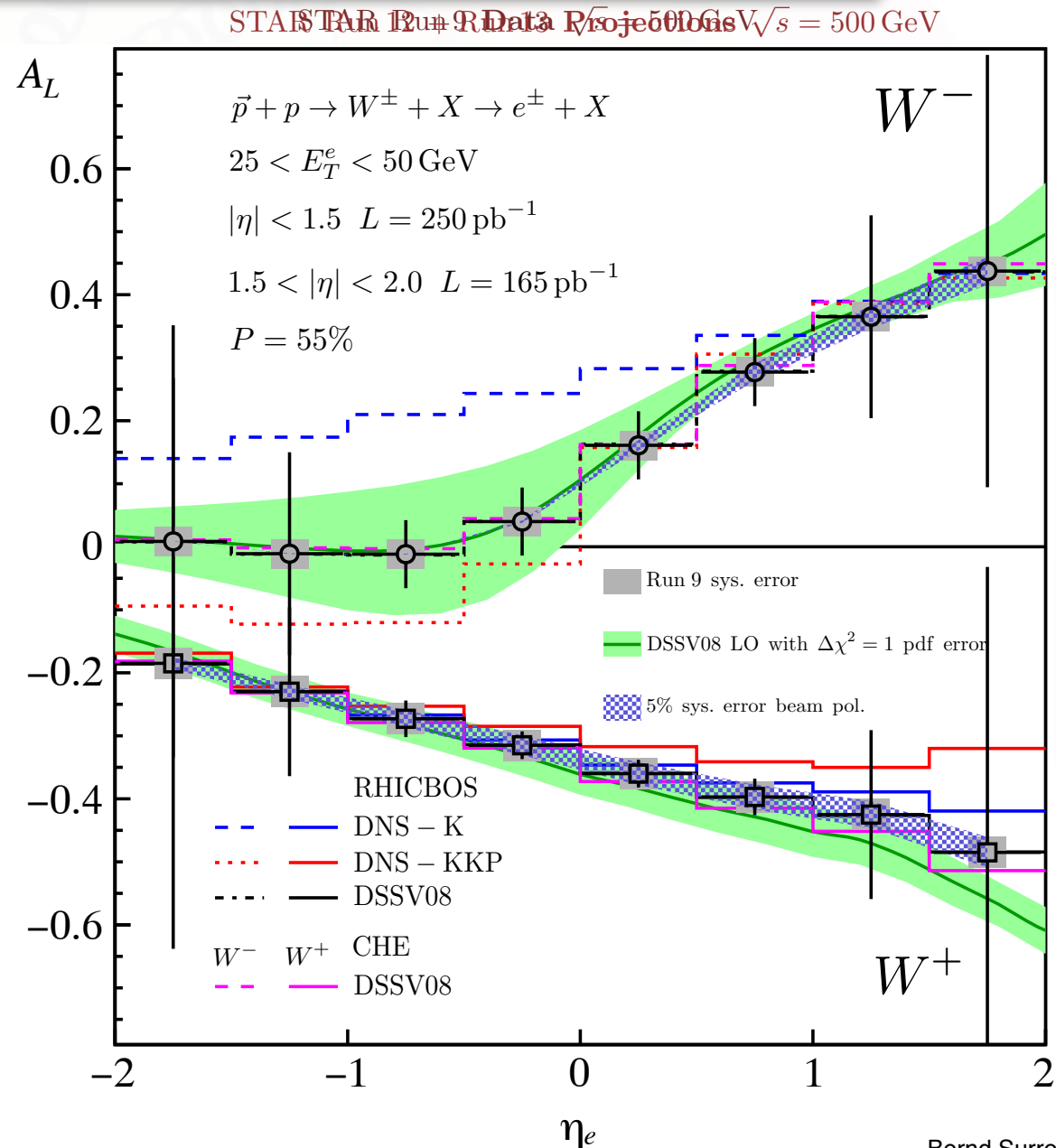
Concepts and Status

□ RHIC W program

Measured asymmetries (Run 9) are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data
 \Rightarrow Universality of helicity distr. functions!

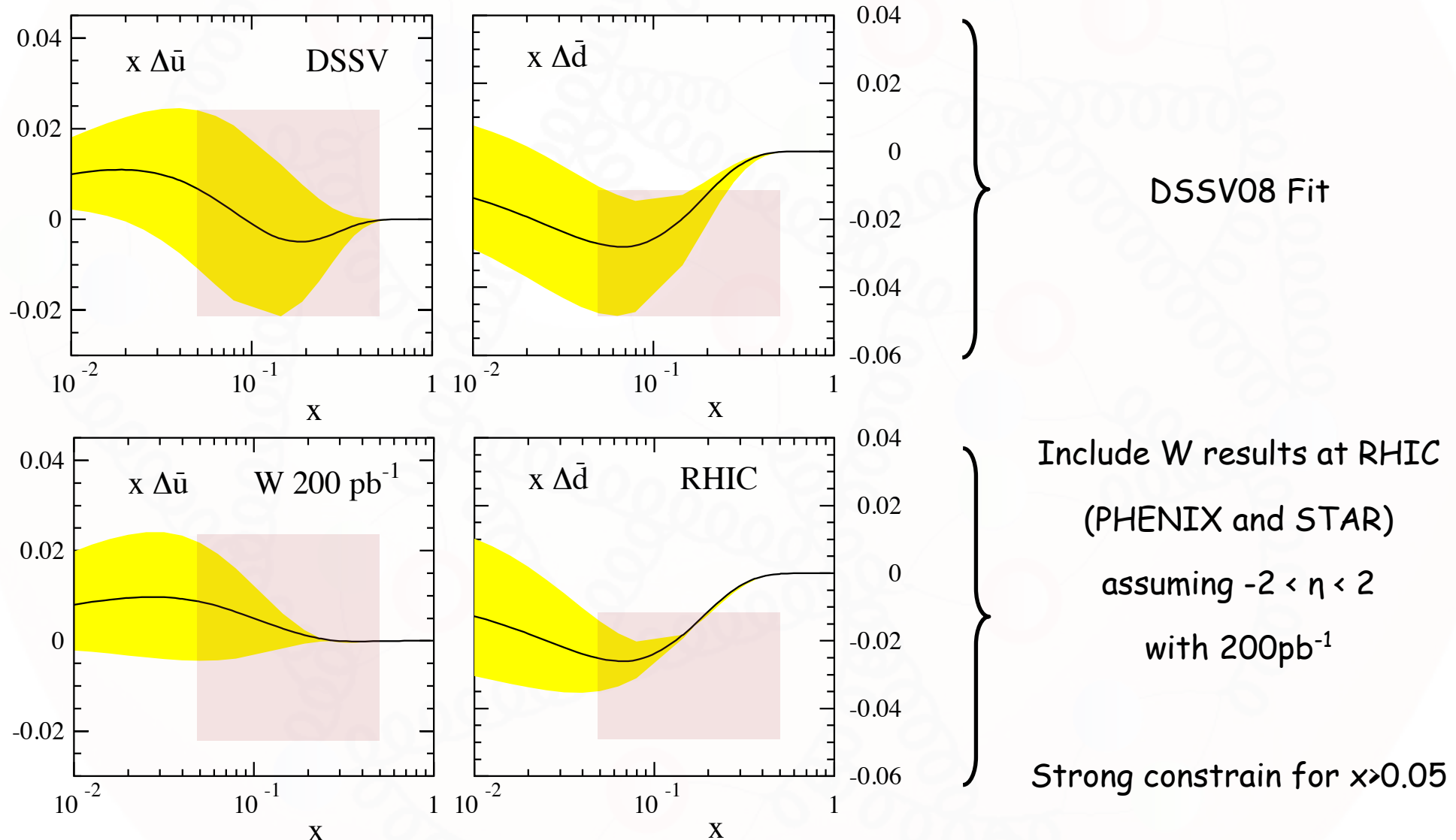
Critical: Measurement of W^+ and W^- asymmetries as a function η_e

Extension of backward / forward η_e acceptance enhances sensitivity to anti-u / anti-d quark polarization
 \Rightarrow PHENIX and STAR forward upgrade!



Concepts and Status

- RHIC W program: Impact on polarized QCD sea D. deFlorian and W. Vogelsang, PRD81, 094020 (2010)



Concepts and Status

- Probing the structure and dynamics of matter in eA / pA scattering

$$Y_+ = 1 + (1 - y)^2$$

$$\left(\frac{d^2\sigma}{dydQ^2} \right) = \frac{2\pi\alpha^2 Y_+}{yQ^4} \left(F_2 - \frac{y^2}{Y_+} F_L \right)$$

$$\sigma_{tot}^{\gamma^*p} = \sigma_T^{\gamma^*p} + \sigma_L^{\gamma^*p}$$

$$F_2 = \frac{Q^2}{4\pi^2\alpha} \sigma_{tot}^{\gamma^*p} = \sum_{f=q\bar{q}} x e_q^2 f$$

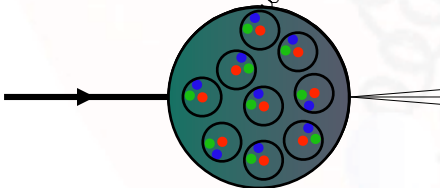
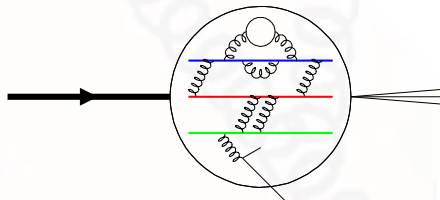
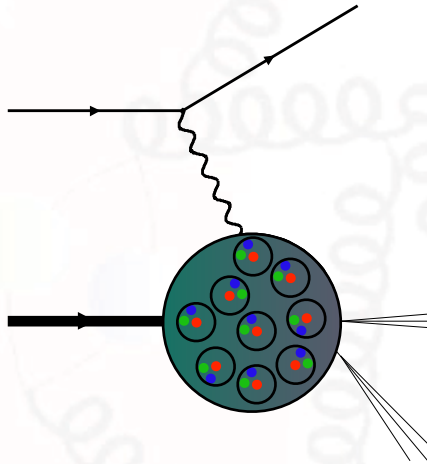
$$F_L = \frac{Q^2}{4\pi^2\alpha} \sigma_L^{\gamma^*p} \propto xg$$

Universality

$$d\sigma = \sum_{f_1, f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \rightarrow f X} \otimes D_f^h$$

Factorization

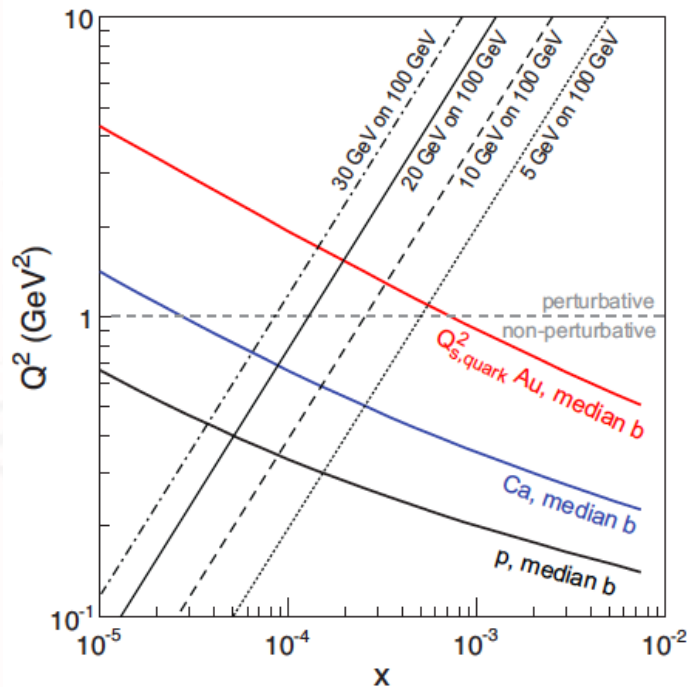
Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!



Concepts and Status

Low-x basics (1)

Dynamics: DGLAP / BFKL and CGC

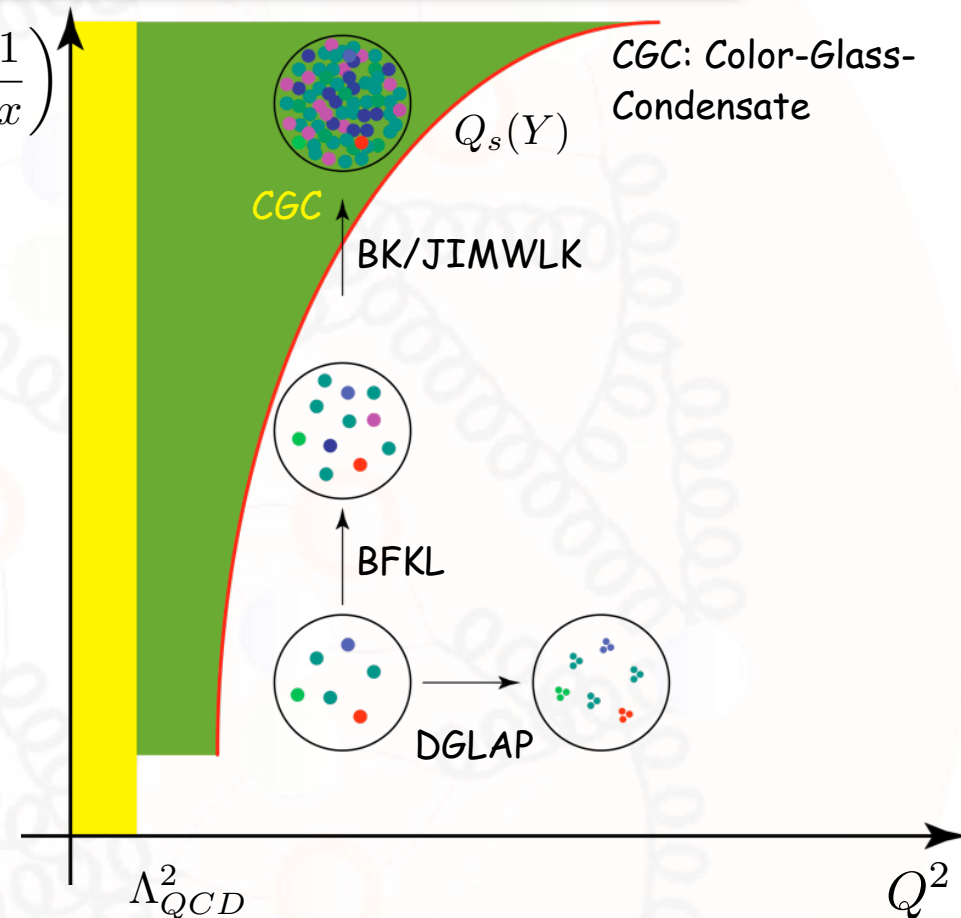


Q_s^2 : **Saturation scale** \Rightarrow Characterize transition to saturation region!

$$Q_s^2 \simeq \alpha_s \frac{1}{\pi R^2} x G(x, Q^2) \sim$$

Enhanced for eA compared to ep: $A^{1/3} x^{-\delta}$

$$Y = \ln \left(\frac{1}{x} \right)$$



$$\Lambda_{QCD}^2$$

$$\alpha_s \sim 1$$

$$\alpha_s \ll 1$$

$$Q^2 > Q_s^2 \Rightarrow \alpha_s = \alpha_s(Q^2)$$

$$Q^2 < Q_s^2 \Rightarrow \alpha_s = \alpha_s(Q_s^2)$$

Concepts and Status

□ Low-x basics (2)

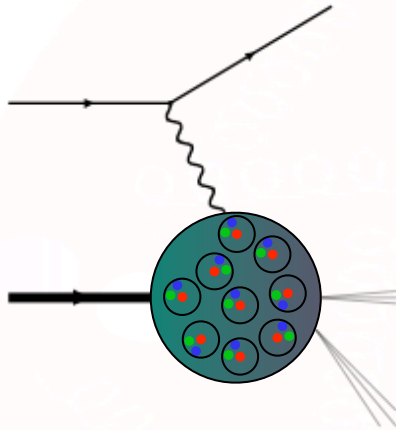
○ Dipole model

Consider **virtual photon-proton cross-section**

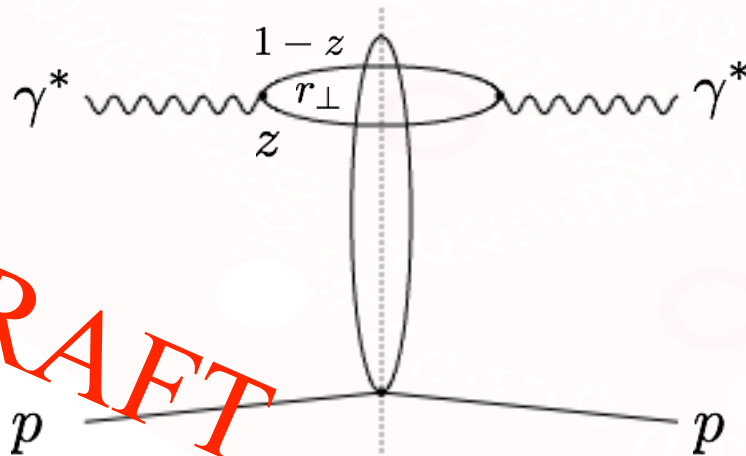
Frame: Proton rest frame

Interaction time < Fluctuation time at **low x**

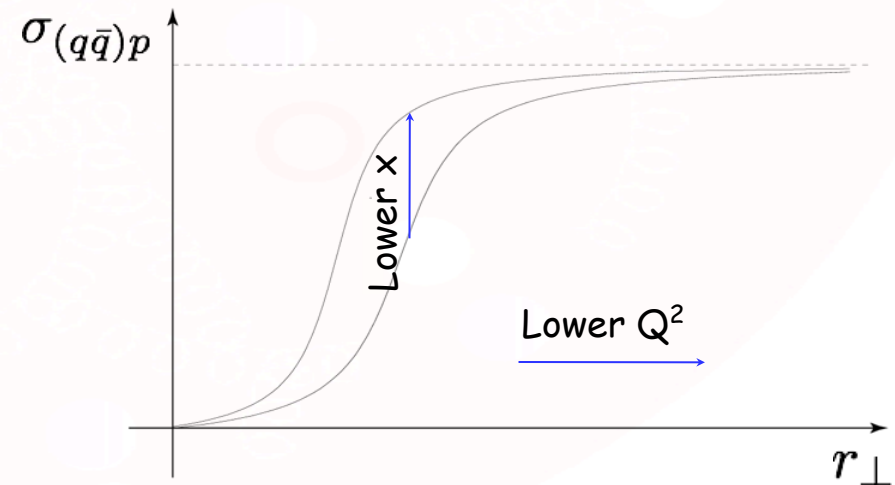
Dipole model: Interaction of quark/anti-quark pair with proton



$$\sigma_{tot}^{\gamma^* p} = \int dz \int d^2 r_{\perp} |\Psi|^2 \sigma_{(q\bar{q})p}$$

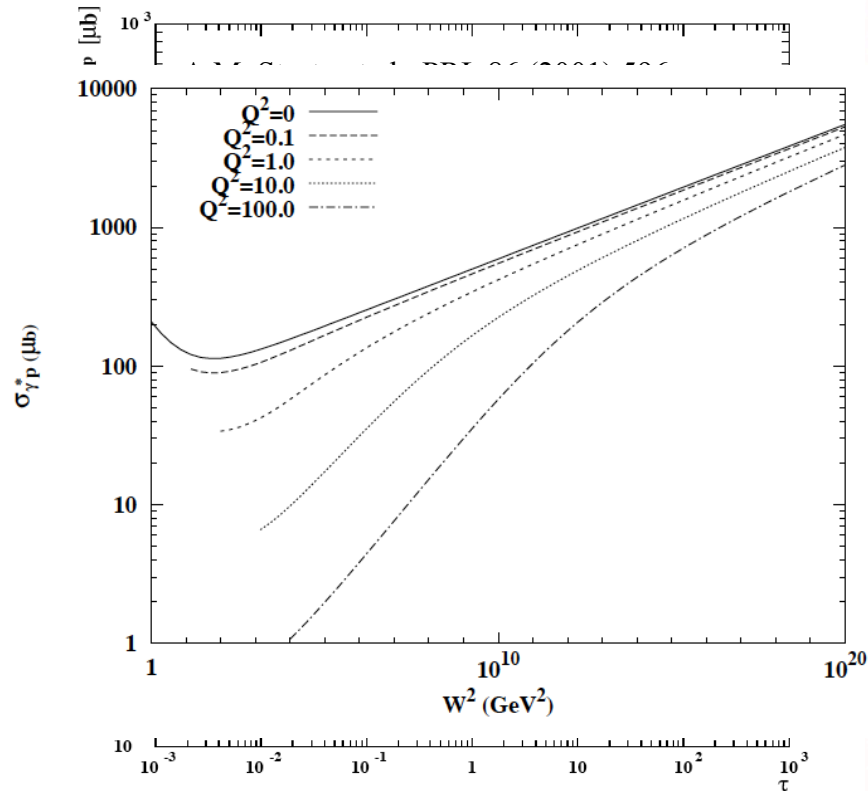


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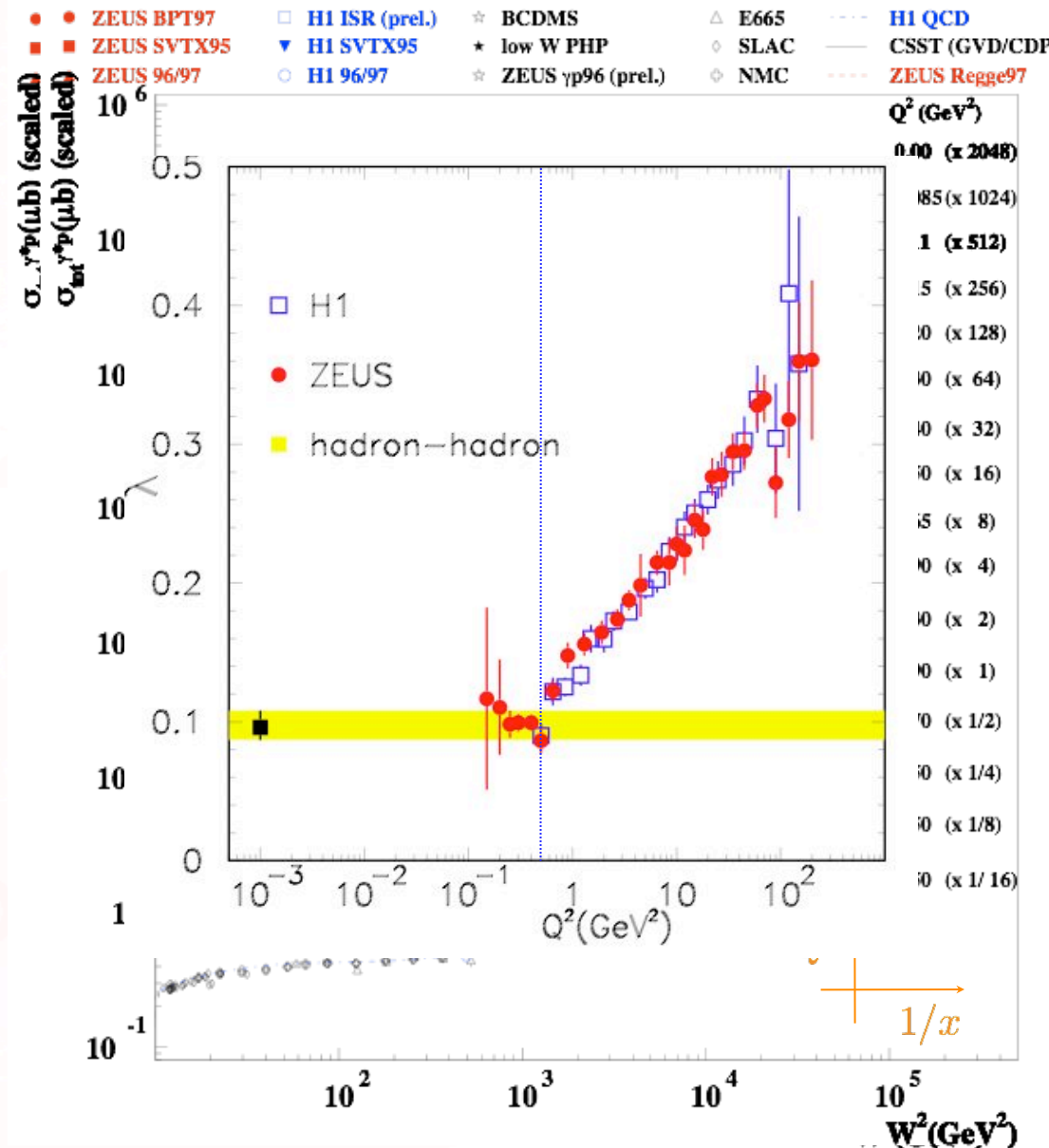
Concepts and Status

HERA: $\gamma^* p$ cross-section



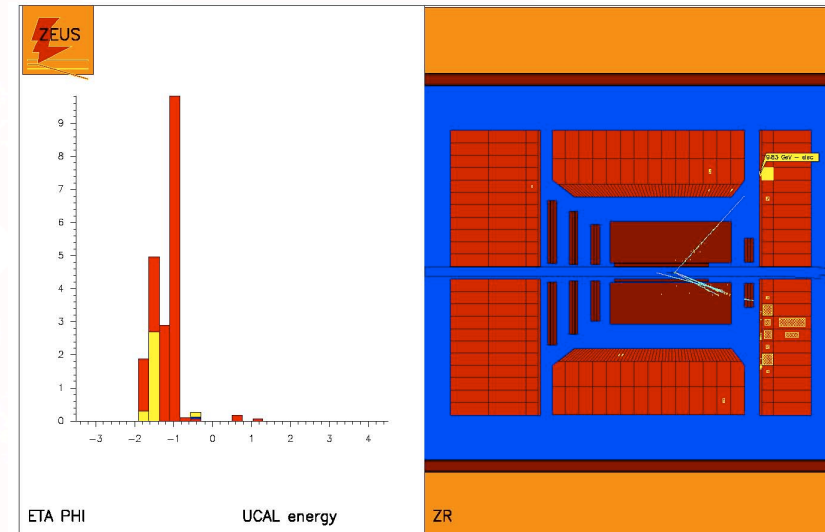
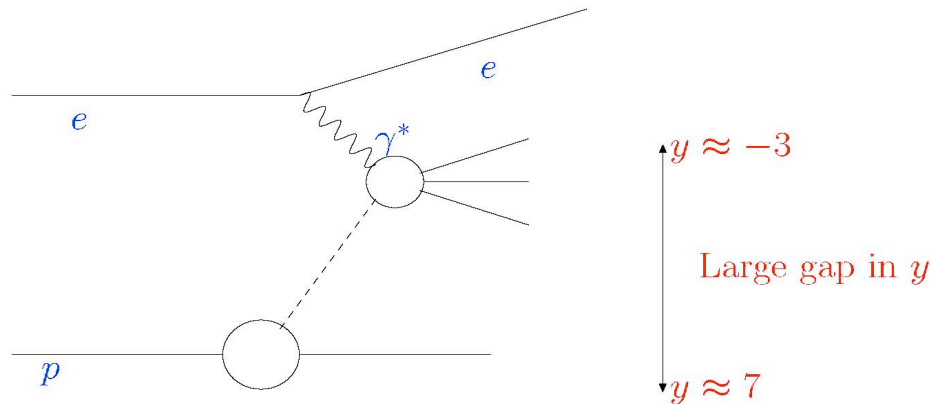
■ Dipole-model approach: Successful description of both inclusive and diffractive processes at low x

■ Change of Q^2 dependence around 1GeV^2 !



Concepts and Status

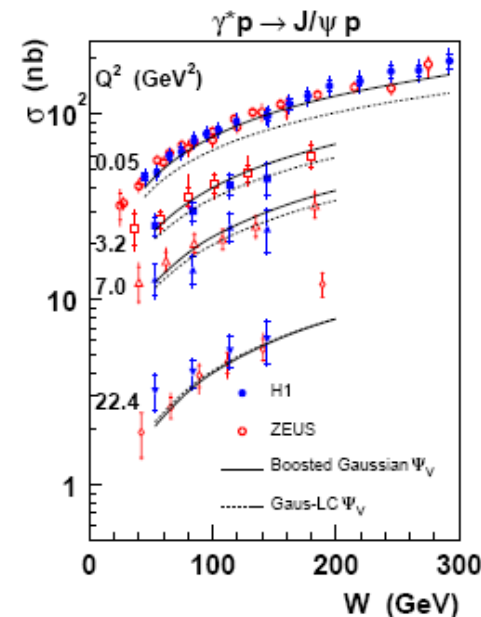
□ Diffraction



○ Ratio of diffractive to total cross-section

($200 < W < 245 \text{ GeV}$): 15% at $Q^2 = 4 \text{ GeV}^2$

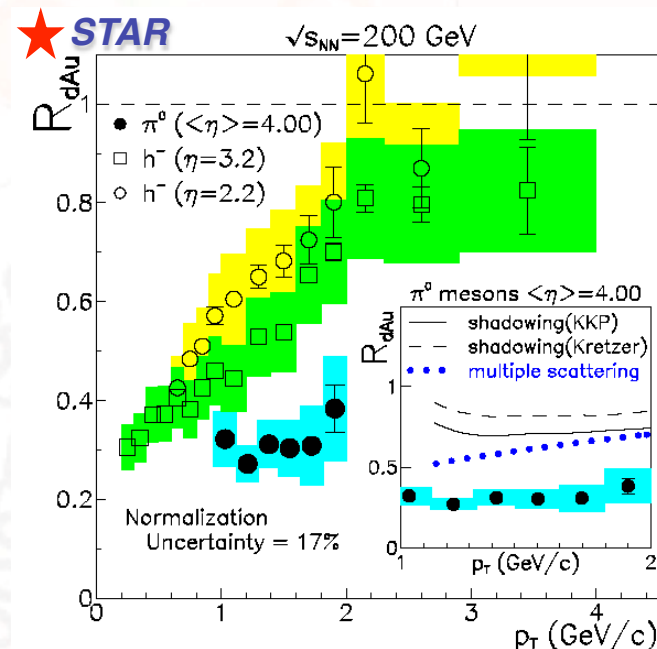
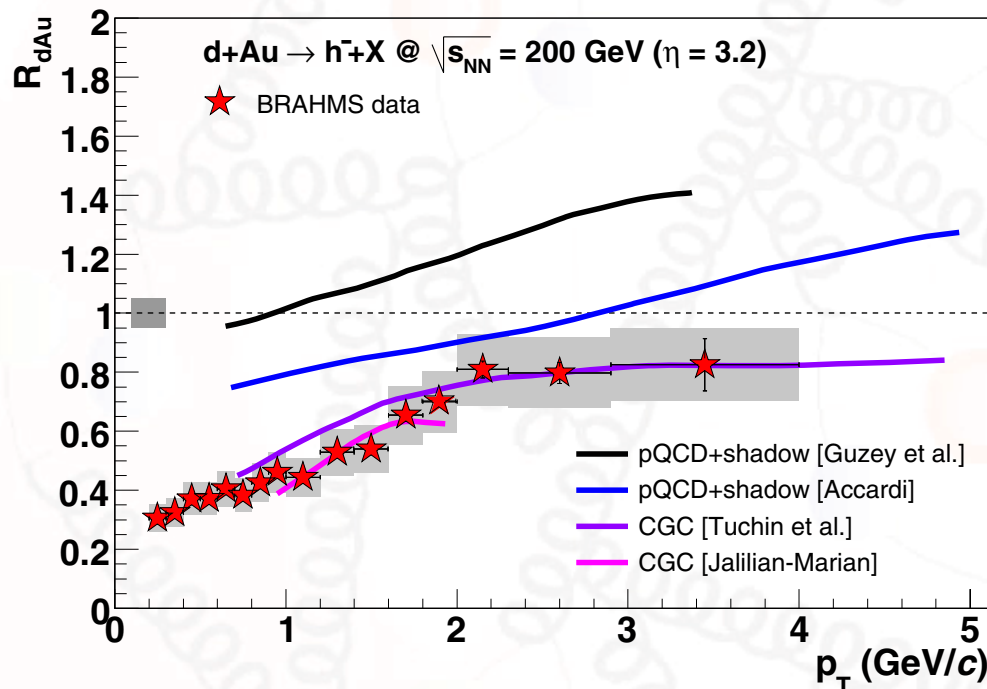
○ Dipole models: Successful description of inclusive and various diffractive measurements (e.g. Ratio of diffractive to inclusive cross-section, Diffractive Vector-Meson production)



$$\propto \alpha_s^2 [g(x, Q^2)]^2$$

Concepts and Status

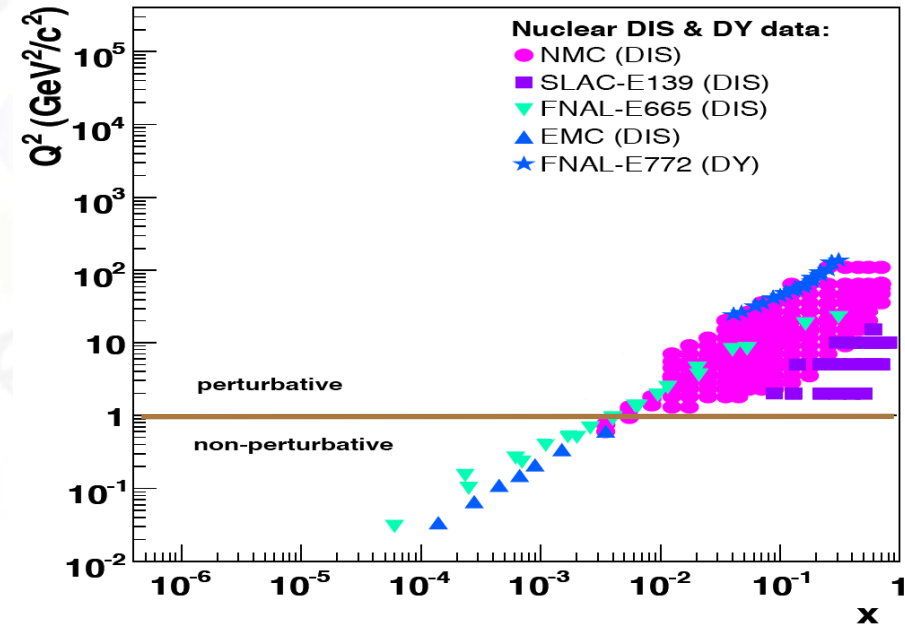
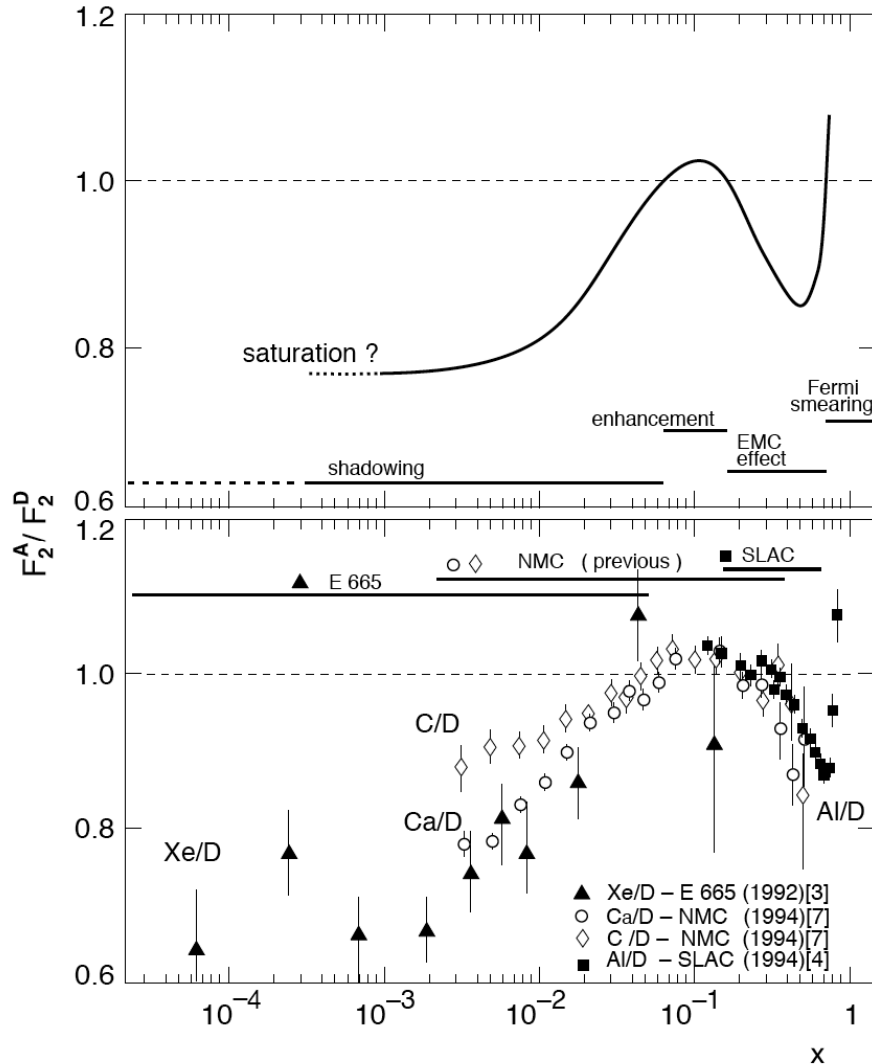
□ RHIC dA scattering at forward η



- Forward identified hadron production at RHIC in dAu collisions: Sizable suppression of yields for charged hadrons and neutral pions observed
- pQCD+shadowing calculations over-predict hadron yield suppression. Is this an indication for gluon saturation in Au nuclei?
- More RHIC dAu are expected with enhanced detector capabilities (PHENIX/STAR)

Concepts and Status

Fixed-target scattering experiments



- Inclusive structure function ratio important to constrain nuclear modifications to gluon density
- World data (Fixed target) are concentrated above $x > 0.01$ in pQCD region
- For $x < 0.01$ only data in non-pQCD region

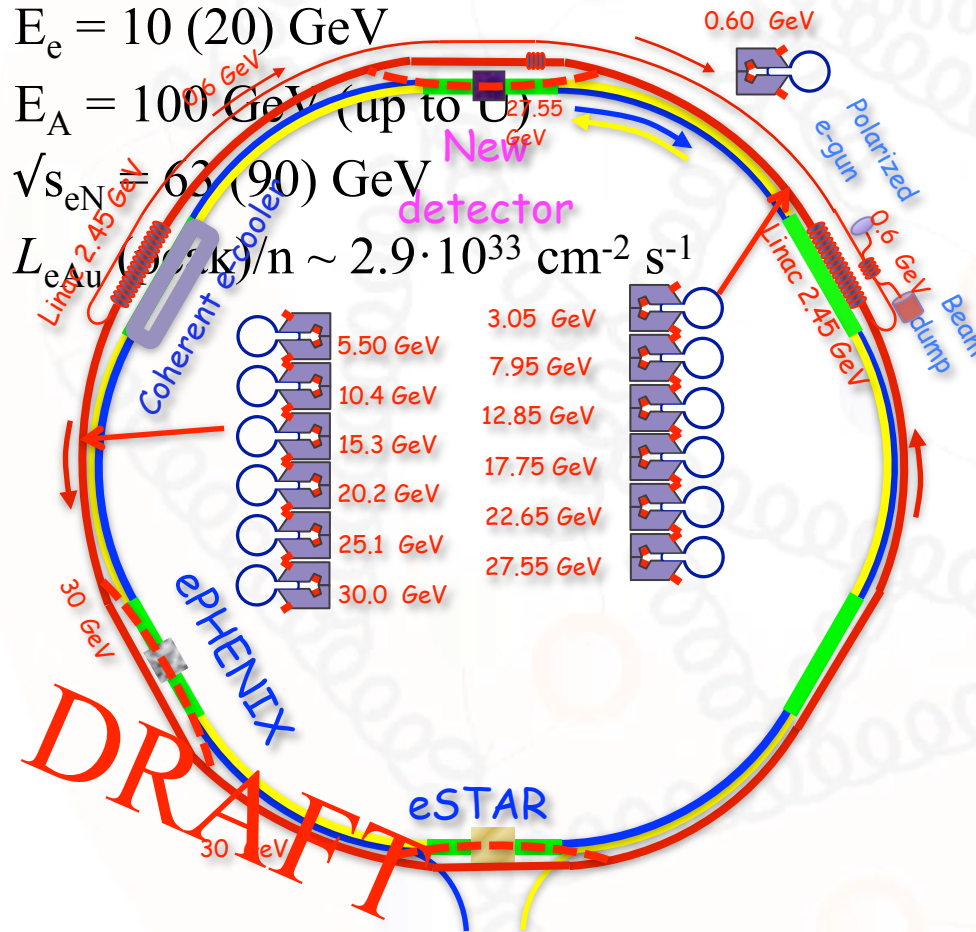
Future opportunities

- EIC facilities

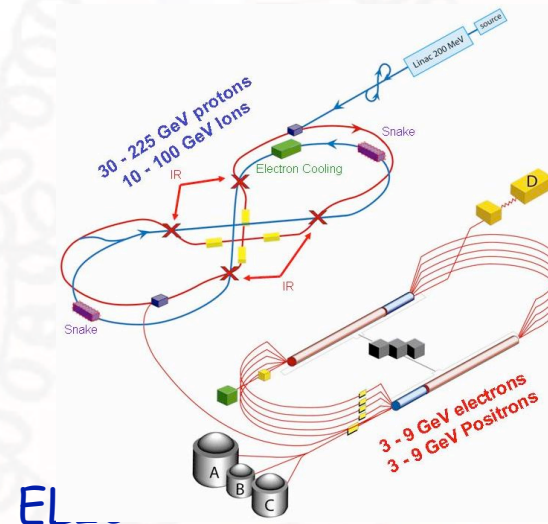
eRHIC (BNL)

$$E_e = 10 \text{ (20) GeV}$$

$E_A = 100 \text{ GeV}$ (up to U)

 $\sqrt{s_{\text{eN}}} = 63 \text{ (90) GeV}$
$$L_{\text{eH}\alpha}(\text{erg s}^{-1})/n \sim 2.9 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$


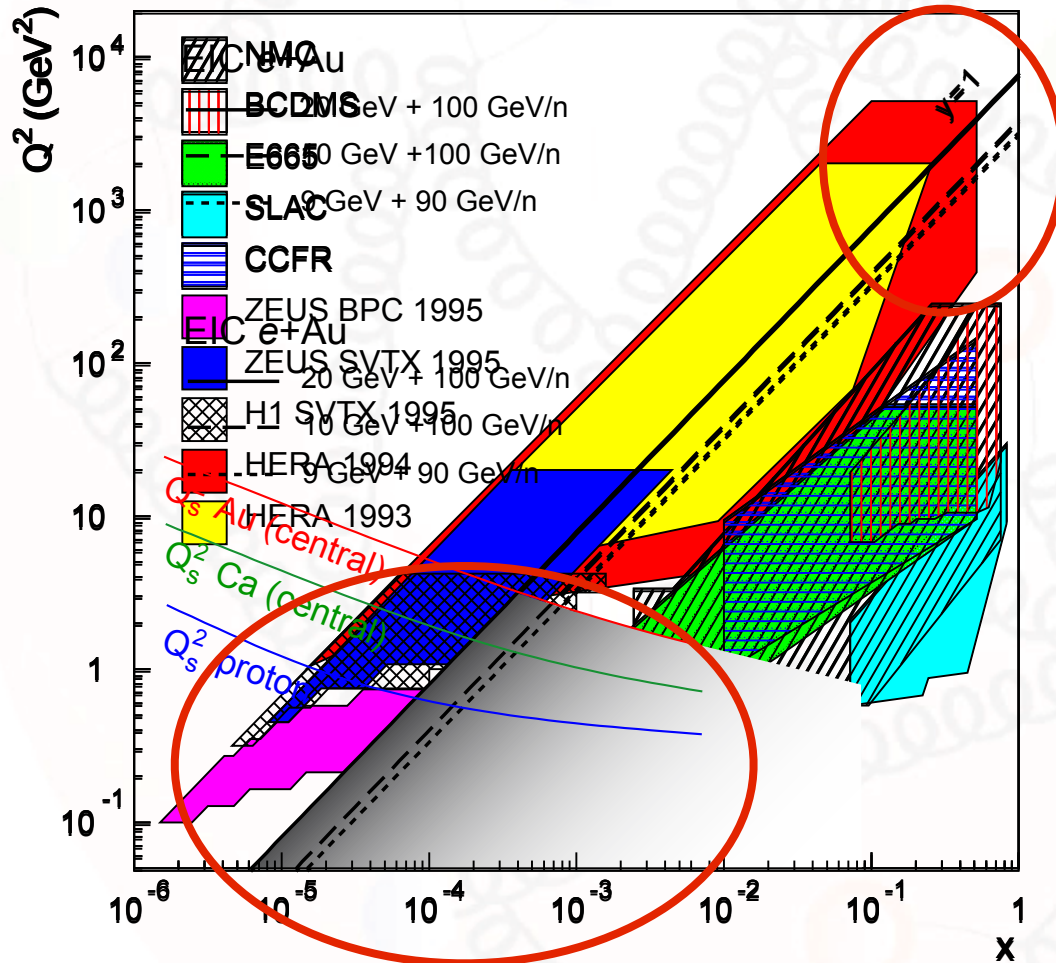
ELIC (JLAB)

$$E_e = 9 \text{ GeV}$$
$$E_A = 90 \text{ GeV (up to Au)}$$
$$\sqrt{s_{\text{eN}}} = 57 \text{ GeV}$$
$$L_{\text{eAu}}(\text{peak})/n \sim 1.6 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$$


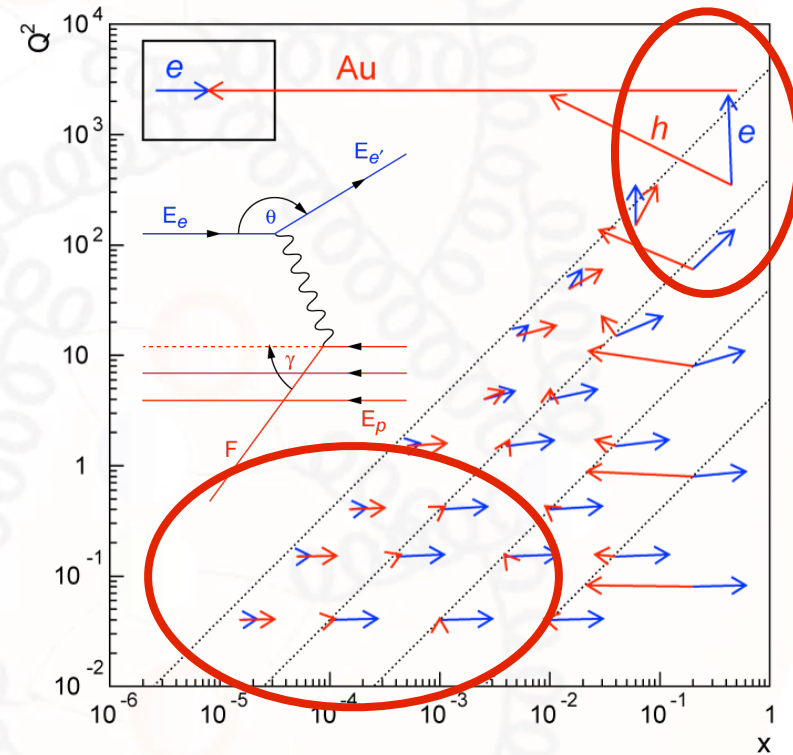
Future Opportunities

Kinematics

Comparison HERA / EIC / Fixed-target experiments



EIC (eA) event topology ($E_e=10$ GeV, $E_{\text{Au}}=100$ GeV)



Terra incognita:

small- x , $Q \approx Q_s$

high- x , large Q^2



Future Opportunities

□ Key observables in electron-proton and electron-nucleus scattering

○ Gluon distribution:

- F_L (Variable center-of-mass energy) and F_2
- Jet rates
- Inelastic vector meson production (e.g. J/Psi)

○ Space-Time distribution of gluon:

- F_L (Variable center-of-mass energy) and F_2
- Deep virtual compton scattering (DVCS)
- Exclusive final states (e.g. Vector meson production)

○ Interaction of fast probes with matter:

- Hadronization, Fragmentation studies
- Energy loss (Heavy quarks)

○ Impact of strong gluon fields on the role of color neutral excitations:

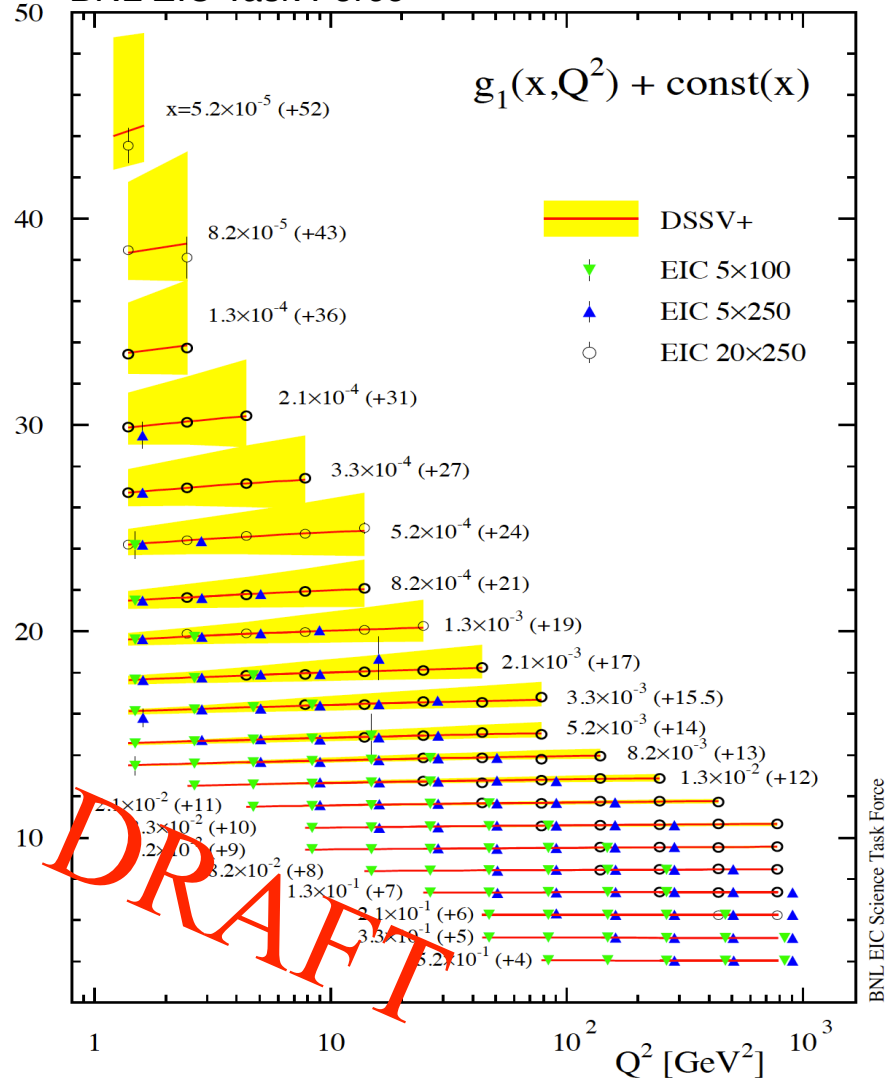
- Diffractive structure functions
- Diffractive vector meson production

DRAFT

Future Opportunities: Polarized ep physics

□ g_1^p at EIC as a function of Q^2

BNL EIC Task Force

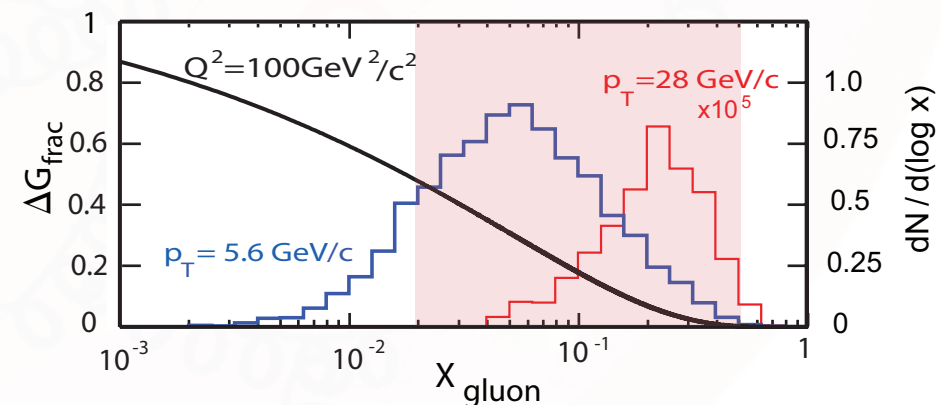
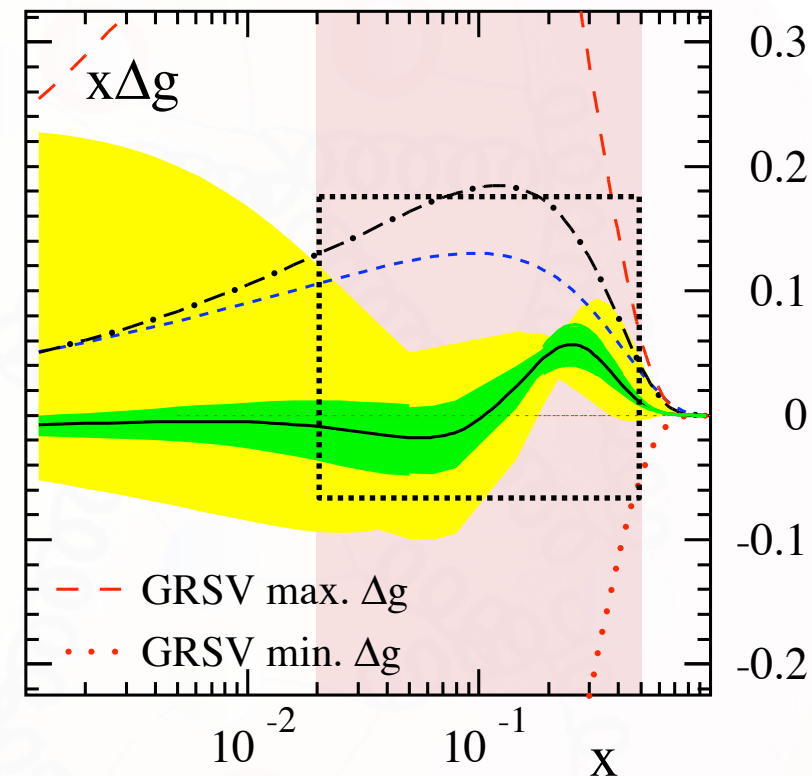
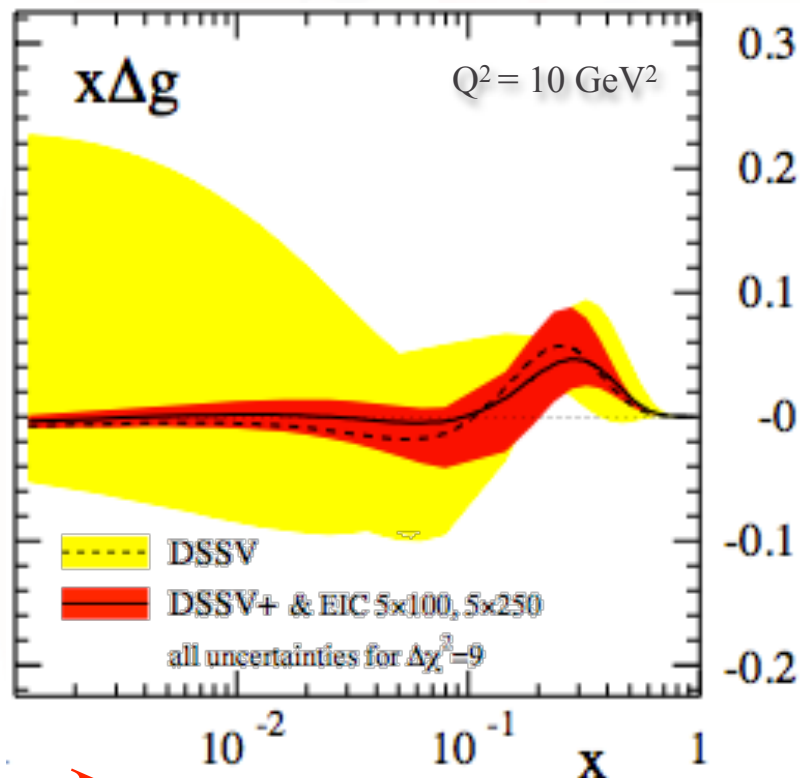


○ Details

Future Opportunities: Polarized ep physics

Impact of EIC on gluon polarization

BNL EIC Task Force

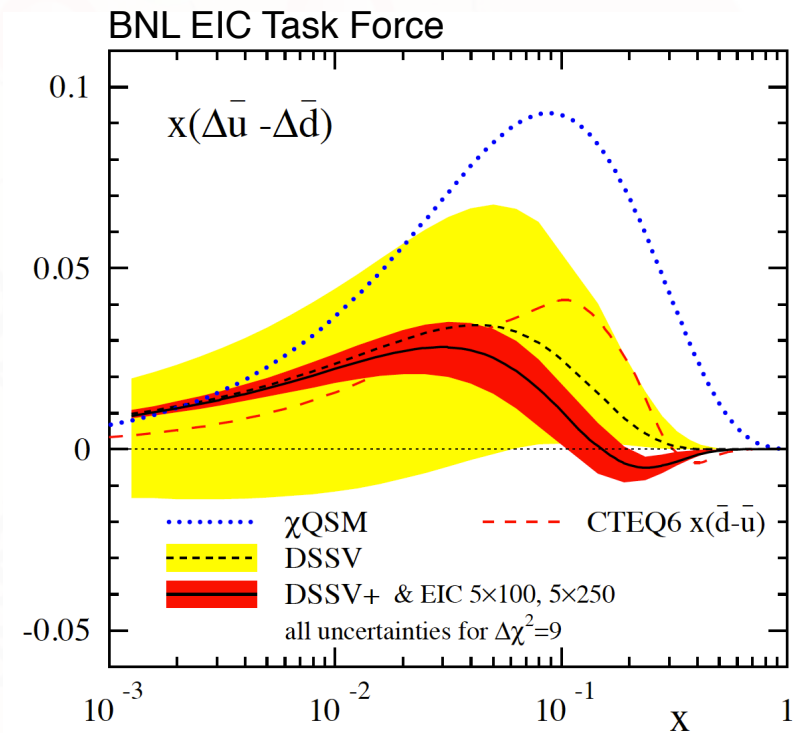
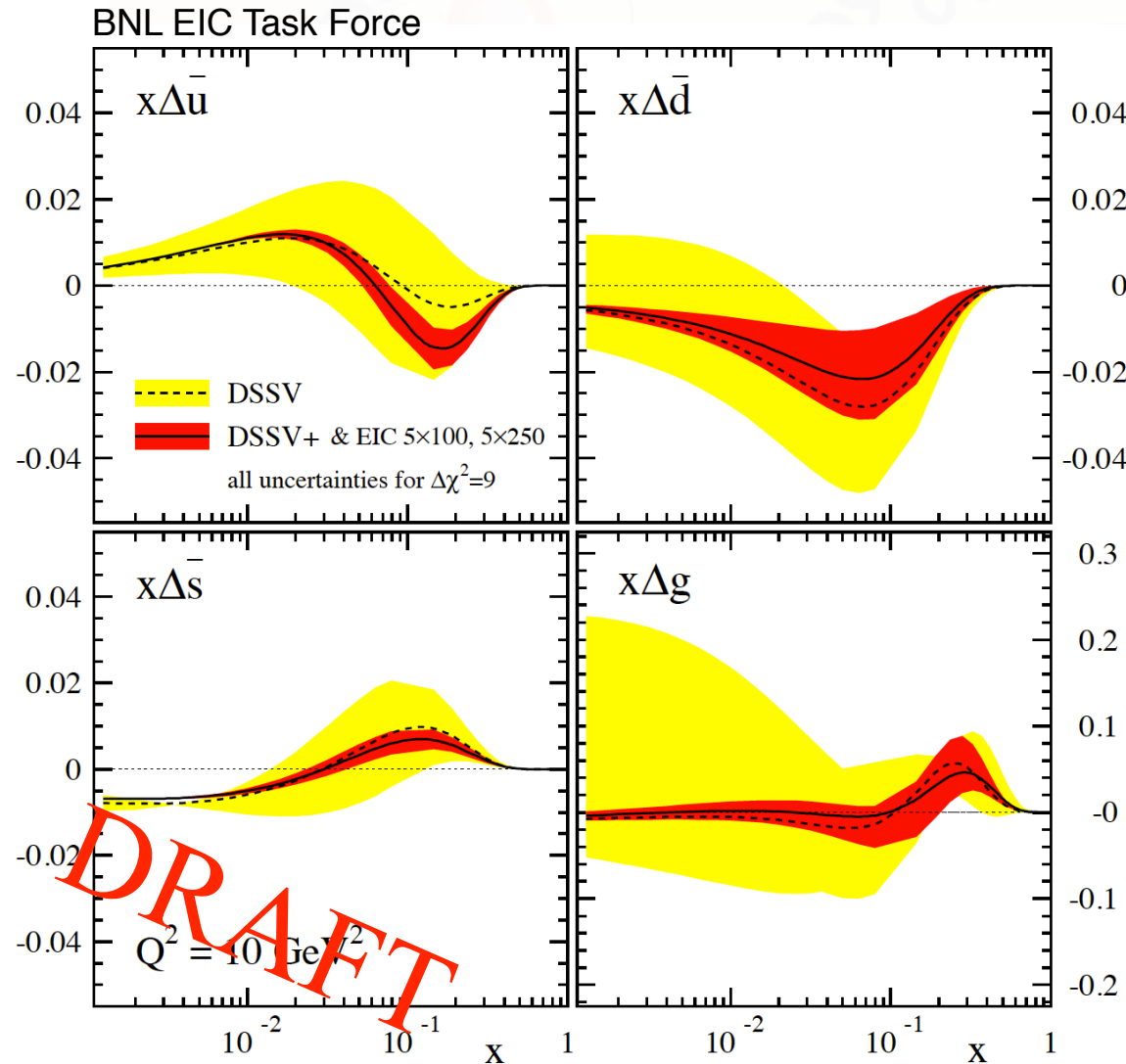


Details

DRAFT

Future Opportunities: Polarized ep physics

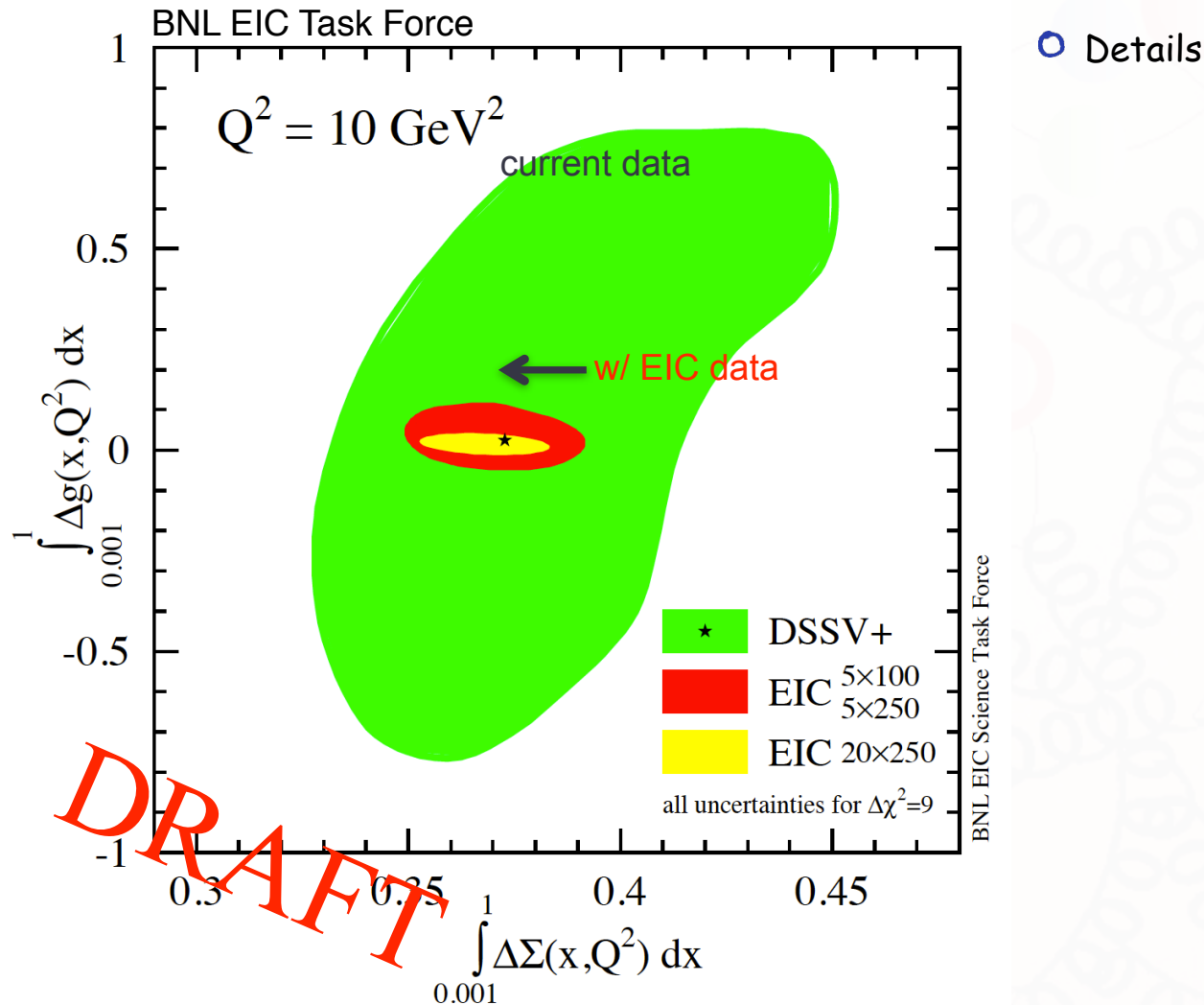
Impact of EIC on quark polarization



Details

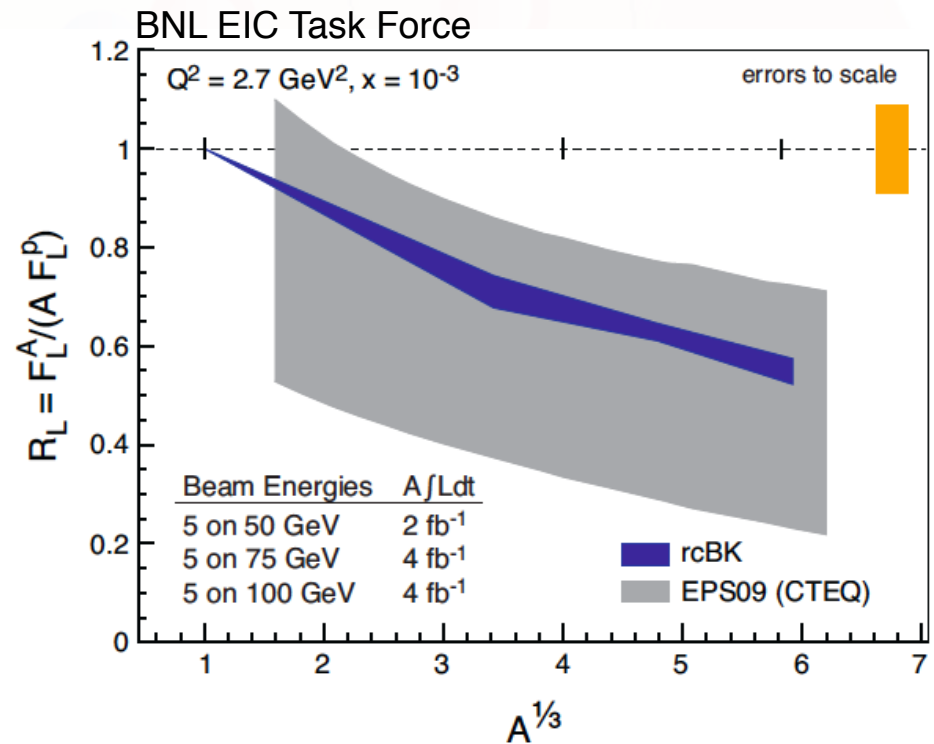
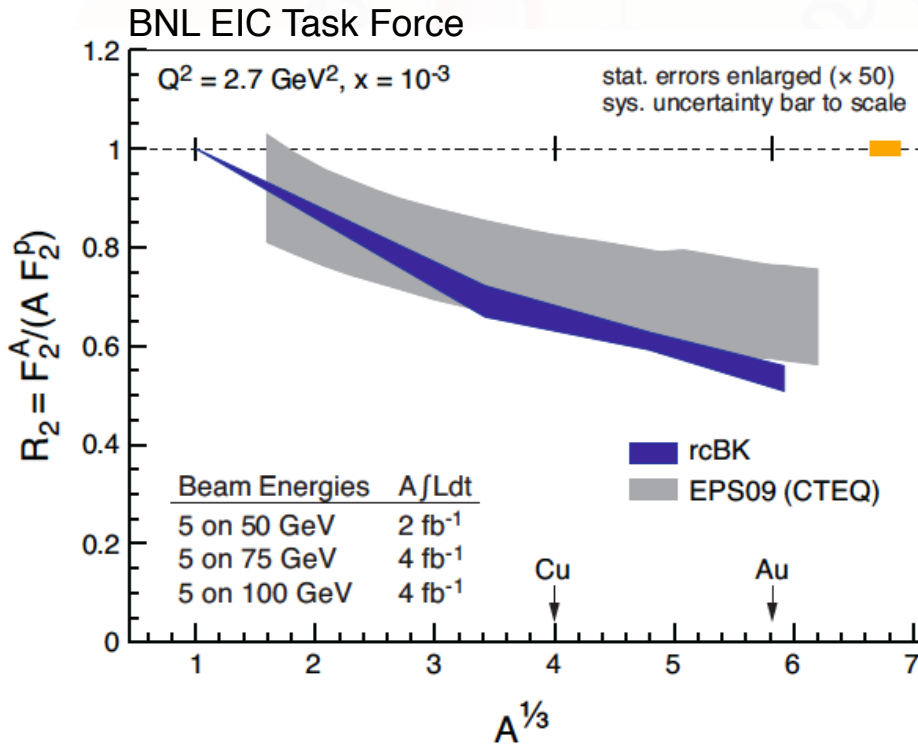
Future Opportunities: Polarized ep physics

□ Impact of EIC on gluon / quark polarization



Future Opportunities: Unpolarized eA physics

□ F_2^A ratio at EIC vs. $A^{1/3}$

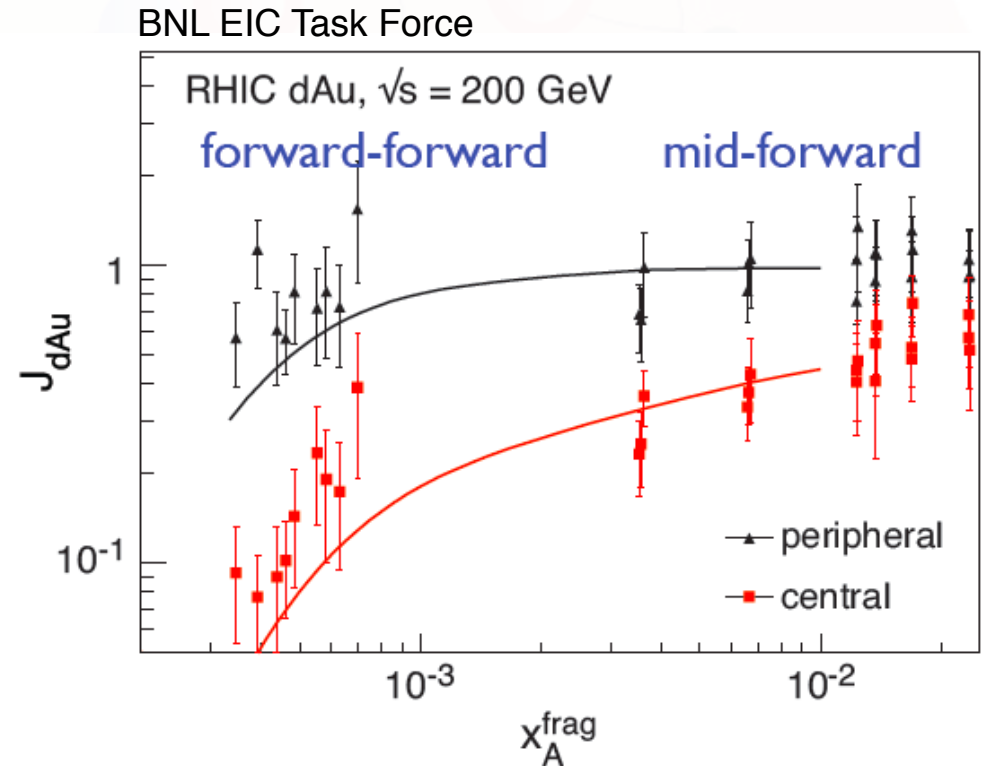
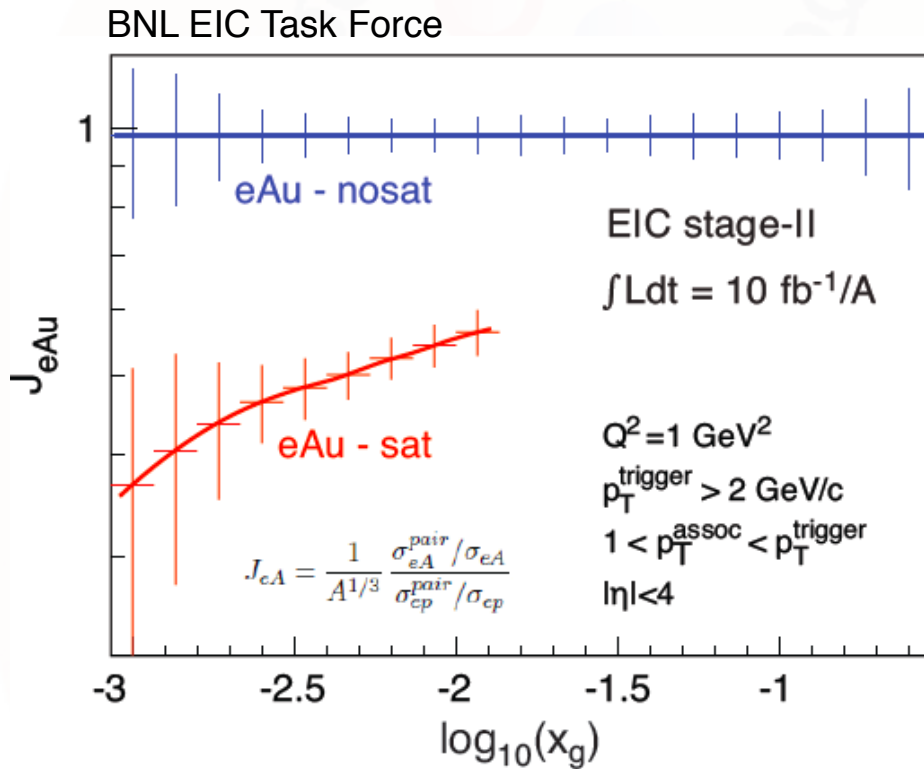


○ Details

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Future Opportunities: Unpolarized eA physics

- Di-hadron correlation vs. x at EIC: Nuclear modification J_{eAu}

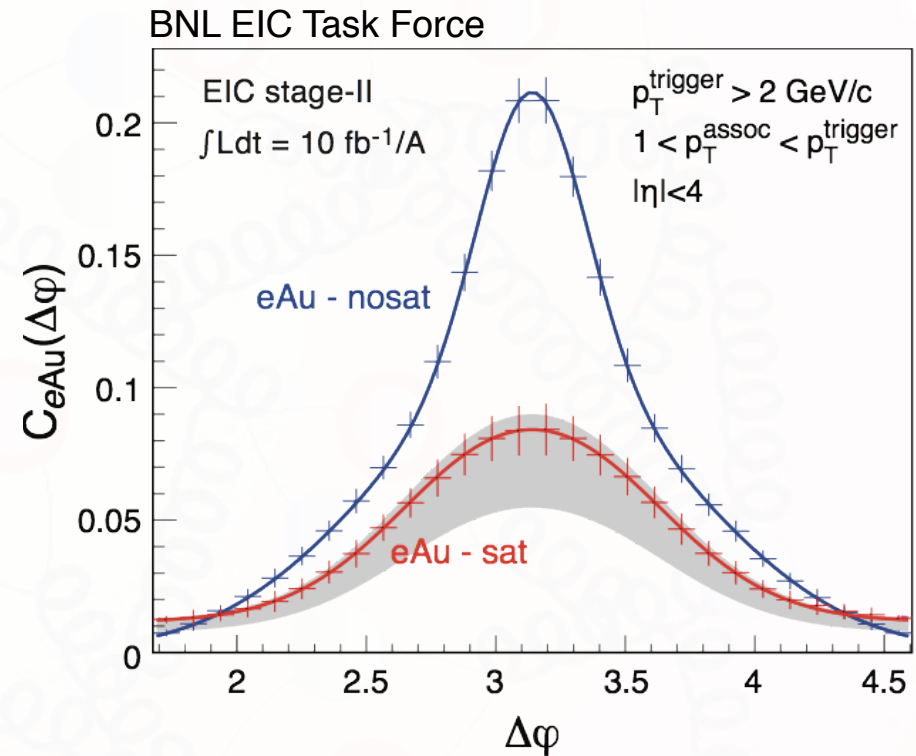
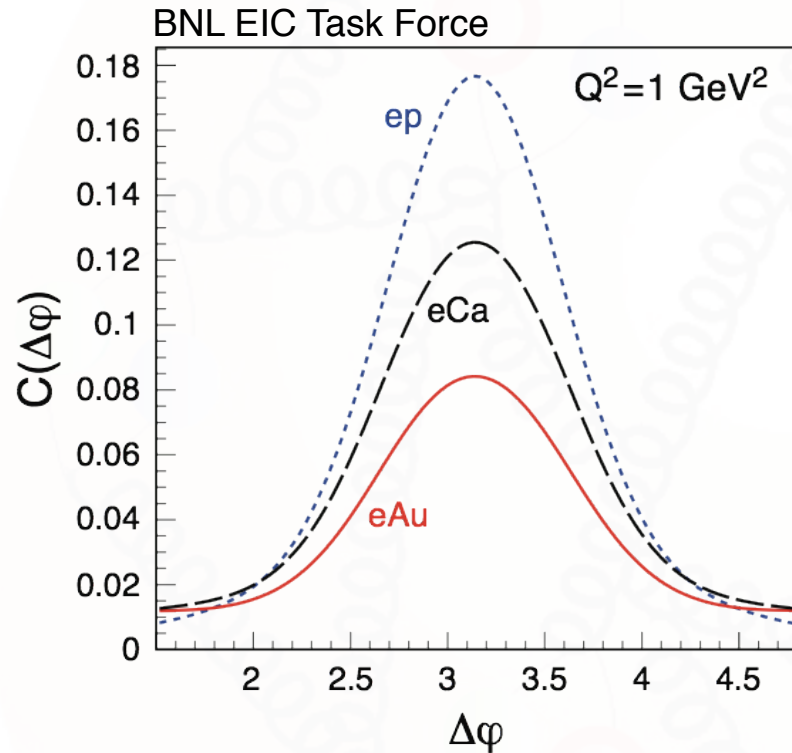


Details

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Future Opportunities: Unpolarized eA physics

□ Di-hadron correlation at EIC



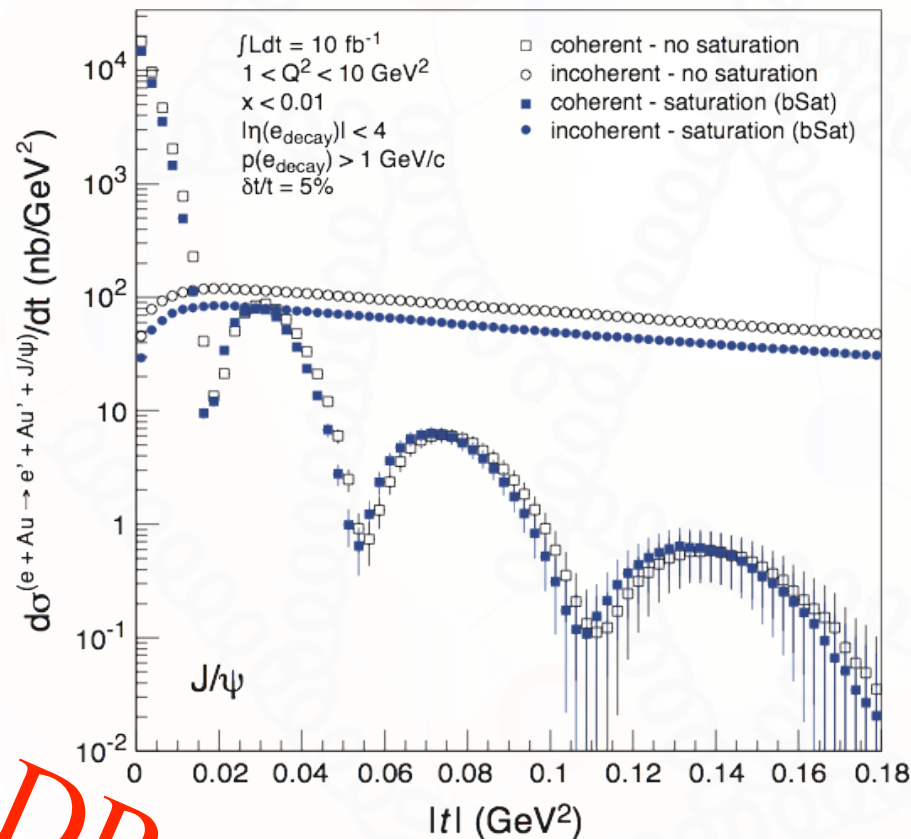
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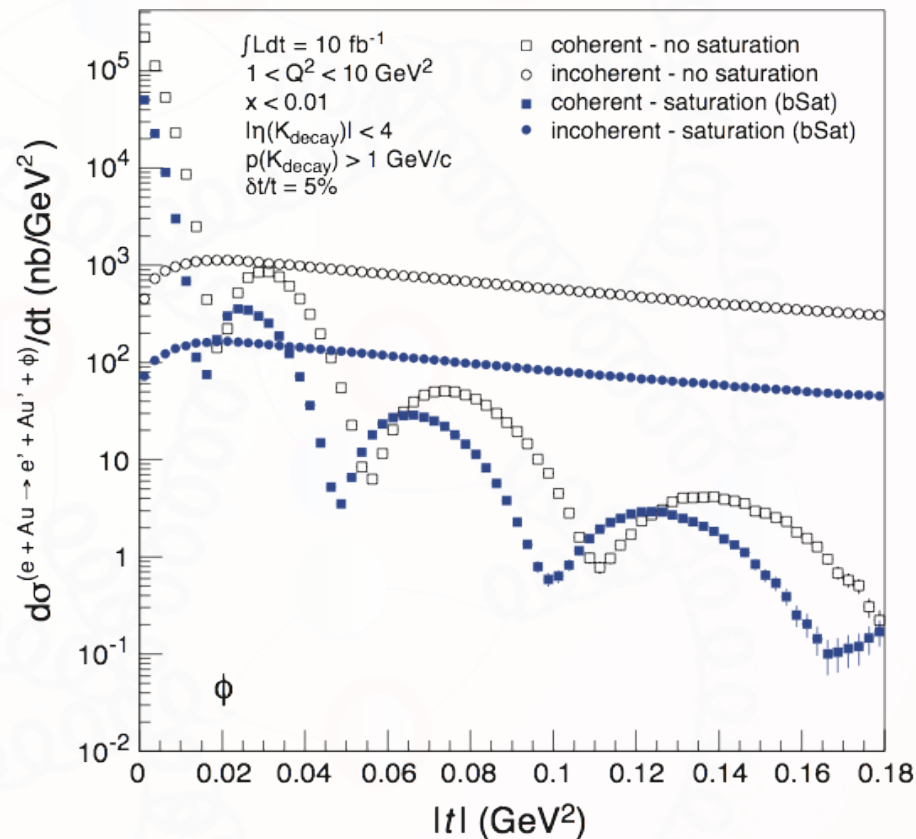
Future Opportunities: Unpolarized eA physics

□ Diffractive VM production at EIC: J/ψ and Φ (1)

BNL EIC Task Force



BNL EIC Task Force

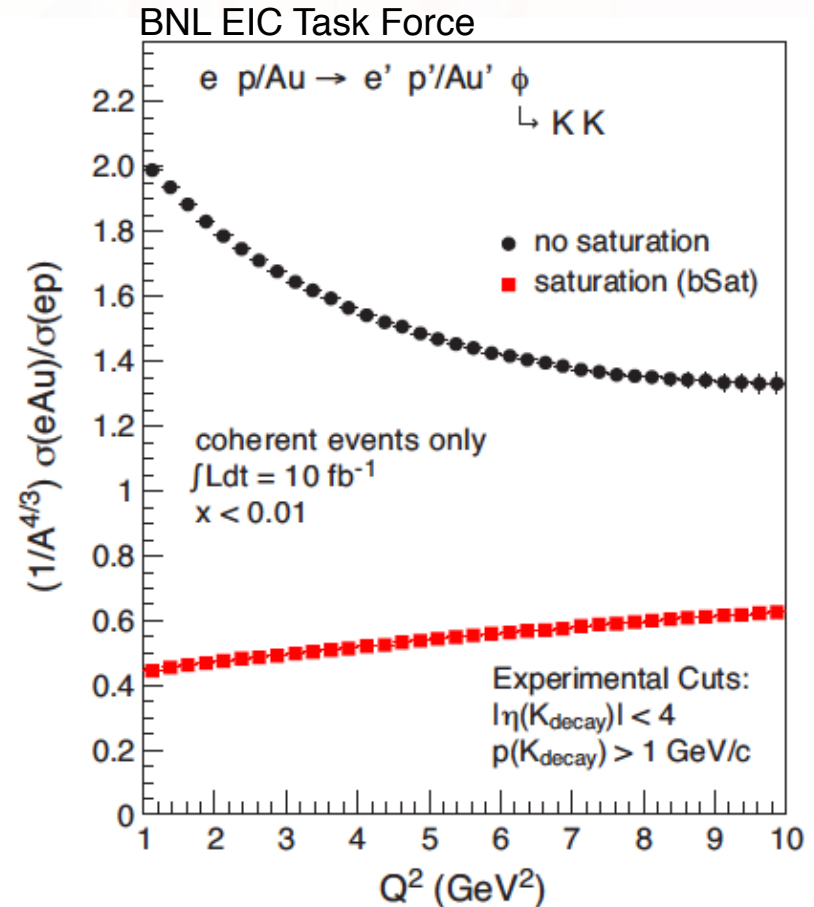
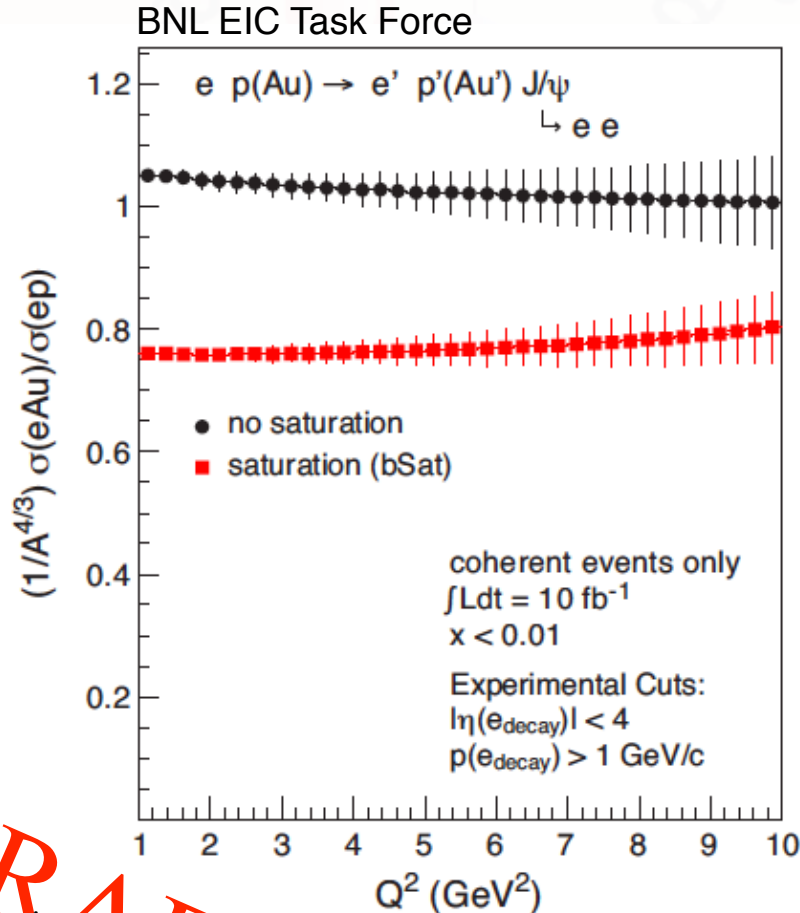


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○ Details

Future Opportunities: Unpolarized eA physics

□ Diffractive VM production at EIC: J/ψ and Φ (2)



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○ Details

Summary and Outlook

□ Status and Concepts

- HERA: Precision structure function measurements (F_2) at low x
- At low Q^2 and low x : DGLAP (Leading twist) approach leads to valence-like gluon behavior
- Diffraction: Important contribution to overall ep event yield
- Dipole model: Allows to describe inclusive and diffractive measurements. Reach of saturation region at low x not conclusive
- Lesson: Optimize any future EIC efforts for acceptance and luminosity
- eA : No information in low- x region
- dAu results at RHIC: Can saturation account for observed behavior? Complementary probes important (RHIC/LHC)!
- Important constrain on gluon polarization at medium and higher x from semi-inclusive polarized DIS and RHIC-SPIN program (Hint for $\Delta G \neq 0$) - Complementary to EIC

Summary and Outlook

□ Future Opportunities

- EIC: First polarized ep collider - Precision measurement of polarized gluon distribution at low- x and quark flavor structure
- EIC will allow to study the physics of strong color fields
- Required: EIC at high luminosity and optimized detector
- EIC will allow to bridge several QCD communities (Hadron structure and Relativistic Heavy-Ion)

